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THE FLOW STARTING PROCESS IN CONSTANT AREA SUPERSONIC DIFFUSERS--ETC(U)
SEP 76 P E MERKLI, N ABUAF F44620-73-C-0032
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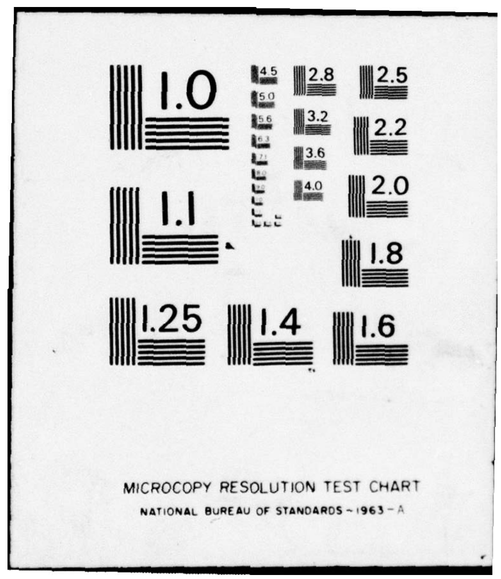
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(6) THE FLOW STARTING PROCESS IN CONSTANT AREA SUPERSONIC DIFFUSERS IN A LUDWIEG TUBE.

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(16) 9781 (17) 03

(9) Scientific Rep[redacted]t no. 5, prepared for AFOSR Research Grant (15) F44620-73-C-0032 "Supersonic Diffuser Research".
"APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED".

DEPARTMENT OF ENGINEERING
AND APPLIED SCIENCE

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ACKNOWLEDGEMENT

The authors would like to thank Professors P. P. Wegener and B. J. C. Wu for their valuable contributions, stimulating and helpful discussions and critical advices. We also gratefully acknowledge Mr. C. F. Lee for his help and Mr. Dennis G. Pelaccio for some well performed experiments. The two-dimensional supersonic nozzle contour was provided by the U. S. Naval Ordnance Lab., White Oak, MD.

ABSTRACT

A Ludwieg tube with a diaphragm located either upstream or downstream of the test section was used to investigate starting times of flow in a M = 3 nozzle followed by a constant area diffuser of square cross section (2 x 2 in^2) with length $0 \leq L/D \leq 6$. The test conditions were $M = 2.8$, $Re_D = 3.6 \times 10^5$, $\delta^*/D \sim 0.04$.*

In the present work the starting time of the supersonic flow at a given location in the supersonic part of nozzle and test section is defined as the time interval required to establish the steady state pressure by a transducer located at the same point, after the initial expansion fan (downstream diaphragm location) or shockwave (upstream diaphragm location) arrives at that point.

For a downstream diaphragm location the starting times were found to be dependent on the diffuser length, but independent of the initial pressure ratio across nozzle and diffuser, as long as this ratio was low enough to allow supersonic flow to be established. For the upstream diaphragm location, the starting times were much shorter than those for downstream diaphragm location. In this second situation, the starting times, however, increased with the pressure ratio across the entire nozzle-diffuser section. For both upstream and downstream diaphragm locations the starting times for supersonic flow at the nozzle exit were longer for the longer diffusers.

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*See Nomenclature on page v.

The lowest overall pressure ratio needed for the flow to start was about 1.2 times the value of the optimum operating pressure recovery ratio for steady flow. The latter ratio was found in previous experiments in a smaller continuous wind tunnel with a geometrically similar nozzle and diffuser. The required diffuser length ($L/D \sim 4.5$) for starting at the optimum pressure ratio corresponds to the expected recovery length of the diffuser as derived from the earlier work with steady flow.

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NOMENCLATURE

a^* - Speed of sound at the throat under critical conditions when M=1.

A - Area, nozzle exit area = $(2 \times 2)\text{in}^2$.

D - Hydraulic diameter at nozzle exit (4 times area divided by perimeter), 16/8 = 2 in.

h^* - Height of the nozzle at the throat, = 0.472 in.

ℓ - Characteristic length of the nozzle, defined as $\sqrt{R^*h^*}$, = 1.89 in.

L - Diffuser length.

M - Mach number.

p - Static pressure.

R - Gas constant.

R^* - Radius of curvature of the diverging section of the nozzle at the throat, = 7.64 in.

Re_D - Reynolds number based on hydraulic diameter and test section free stream parameters, = $v\rho D/\mu$.

t - Time.

$\bar{t}_s$ - Dimensionless starting time, $\equiv t_s/\tau_f$

T - Temperature.

v - Flow speed.

x - Axial distance, nozzle exit x = 0.

γ - Ratio of specific heats.

δ^* - Boundary layer displacement thickness.

ρ - Density.

μ - Dynamic viscosity.

τ_f - Characteristic flow time, defined by ℓ/a^*, = 0.153 ms.

Subscripts

1 - Downstream initial conditions before diaphragm rupture.

4 - Upstream initial conditions before diaphragm rupture.

3 - Conditions upstream of nozzle after the expansion fan has passed into the supply tube.

0 - Nozzle supply conditions.

n - Conditions at the nozzle end.

d - Conditions at the diffuser end.

during first cycle of the Ludwieg tube flow.

I. INTRODUCTION

The pressure recovery of supersonic diffusers attached to narrow ducts as encountered in applications such as those of gasdynamic lasers cannot be markedly improved by refined diffuser designs (Merkli, 1975a). This is especially true if a diffuser of a certain contour does not operate at the proper design specifications. Moreover, parallel rows of such diffusers have been proposed (e.g. Russell, 1975) and consequently the simplicity of the diffuser geometry becomes a key factor in practical applications. Hence, the straight duct supersonic diffuser emerges as an attractive possibility and new interest in its performance under various conditions has arisen.

The primary performance criterion of a diffuser is the optimum pressure recovery if operating at its design point. The required diffuser length to obtain this optimum pressure recovery is also of practical importance. These two topics have been investigated in earlier years by Neumann and Lustwerk (1949), and more recently by Waltrup and Billig (1973) and Davidson and Chukhalo (1969). For narrow flow channels this work was extended by Merkli (1975b, 1976). For some applications an additional important performance criterion arises. Here the period of time required to get the flow started to achieve a steady state in the supersonic nozzle-diffuser assembly is of interest.

This report primarily addresses itself to the latter point, the determination of the starting times for straight duct diffusers of various lengths. Experiments along similar lines have been carried out

in a Ludwieg tube (Ludwieg, 1955; Cable and Cox, 1963) in our laboratory previously (e.g. Johnson and Cagliostro, 1971; Cagliostro, 1972; Smith and Mosnier, 1973). The Ludwieg tube, shown schematically in Fig. 1a, consists of a shock tube attached to a converging-diverging nozzle to generate supersonic flow in a test section. In fact, the tube is a simple intermittent supersonic wind tunnel. For the reported experiments the diaphragm separating a high and a low pressure section was located either downstream of the diffuser or upstream of the nozzle (Fig. 1). Simplified x-t diagrams indicating the flow process after diaphragm rupture are also presented in Figs. 1b and 1c for both diaphragm locations (Falk and Hertzberg, 1967). Here the nozzle has been simplified to a zero-length converging-diverging nozzle followed by a constant area test section. When the diaphragm is in the downstream position, the flow starting time at a given location in the nozzle is known to depend upon the nozzle geometry and the diaphragm location (Johnson and Cagliostro, 1971; Cagliostro, 1972; Smith and Mosnier, 1973). The starting time at a given location is defined for this purpose as follows. The starting time is the time period counted from the time the first pressure change from the initial value occurs with the arrival of the initial expansion fan (downstream diaphragm) or shock wave (upstream diaphragm) until the steady state pressure level is achieved. This starting time definition is strongly dependent on location and implies that different starting times will prevail at the nozzle throat and at the nozzle exit. Thus it is important to cite and specify the location with each starting time value. In the present experiments conducted with the diaphragm located downstream

of the diffuser, the starting time of the fully developed supersonic flow at the nozzle exit was found to depend on the length of the straight duct diffuser ($0 \leq L/D \leq 6$)*. The diffuser with the better pressure recovery during steady state operation required a longer starting time. Yet for a given geometry and diffuser length, the starting time is essentially independent of the initial diffuser back pressure as long as this pressure is low enough to permit proper starting of the fully developed supersonic flow through the nozzle.

In the first set of experiments with the downstream diaphragm location, the supply and back pressure of nozzle and diffuser varied stepwise due to the returning reflections of the expansion waves from the end of the upstream tube section, and of the shock waves from the downstream tube end. However, some information on an apparent diffuser back pressure differences in flow starting and breakdown is gained here by comparing the present results with the earlier ones obtained by Merkli (1975b, 1976). This comparison is valid since in both investigations the same supersonic nozzle design was used. Unfortunately, these comparisons are not wholly valid because the pressure levels (upstream and downstream) during the "steady" operation period of the Ludwieg tube (in the present experiments only the first cycle was used**), are not as steady as those of the continuous tunnel. In a Ludwieg tube and other short duration intermittent facilities it is therefore not possible to

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*For symbols see Nomenclature on page v.

**For definitions of the flow cycles, etc., note the references given on the Ludwieg tube (Cable and Cox, 1963).

decide unambiguously when the supersonic flow is started. Moreover, it is known that near optimum performance conditions, the diffuser flow is exceptionally sensitive to small disturbances.

In order to improve the deleterious effects of the disturbances caused by the shock wave reflections from the downstream tube end, the downstream section of the Ludwieg tube was connected to a dump tank with a volume of 17 cubit feet as seen in Fig. 1a. With this configuration the duration of steady flow in the test section was governed by the upstream conditions in the driver section, again using only the first cycle of the Ludwieg tube flow. The results of starting times and limiting pressure ratios for various diffusers obtained with the dump tank agree closely with the previous data obtained without the dump tank.

Experiments were also conducted with the diaphragm located in the upstream position of the test section. As previously reported in the literature (Falk and Hertzberg, 1967; Davis, 1968), the starting times for the supersonic flow to be established at the nozzle exit were found to be much shorter than those obtained with the downstream diaphragm (see Fig. 1b, c). In the case of upstream diaphragm location, the starting times for a given diffuser length increased steadily with the pressure ratio across the nozzle-diffuser assembly. For a given constant initial downstream pressure the starting times increase as the diffuser length is increased. The optimum pressure ratios for operation of the nozzle with steady supersonic flow during the first cycle, present a similar variation with diffuser length as the results obtained with the downstream diaphragm experiments.

With the Ludwieg tube test section designed for the diffuser research and offering an excellent view of the nozzle and diffuser flow, high speed schlieren movies of the flow were also taken for the downstream diaphragm configuration. The results on flow Mach numbers and starting times taken from such movies agreed with those obtained from the usual pressure measurements.

II. EXPERIMENTAL

A. THE TEST FACILITY

The experimental set-up is seen in Figs. 1 and 2. Both, the driver and driven sections of the Ludwieg tube have 90° bends in order to accommodate the required tube length in the laboratory. With the speed of sound roughly 1 ft/msec, every foot of tube length of the driver section gives approximately 2 msec of steady running time in a given cycle*. The 90° bends of the tube do not substantially impair the overall performance, yet some weak reflections of shock waves from the T-shaped tube section (Fig. 1a) were noted. Such shock wave reflections complicated the evaluation of the earlier diffuser data at high pressure ratios, since the diffuser flows are highly sensitive to small disturbances. In the later experiments the connection of the dump tank reduced and eliminated some of these limitations and disturbances.

The tube cross section is circular and the upstream and downstream

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*The duration of the cycle is given by the period defined by the expansion fan's return to the nozzle entrance.

sections are made from seamless stainless steel tube with inside diameters of 3.76 and 5.295 in respectively. The test section has a rectangular cross section (2 x 5) in^2. As seen from Fig. 2a, two transition pieces on either side of the test section connect the circular and rectangular ducts. In the experiments discussed here, the diaphragm was located at both the downstream as well as the upstream ends of the test section. Two layers of 0.002 in thick cellophane sheets were used as the diaphragm material in the experiments conducted with the downstream diaphragm location. The diaphragm in this case was ruptured by a spring actuated pin mechanism. In the experiments conducted with an upstream diaphragm location a 0.003 in thick MYLAR sheet was used as the diaphragm material. The MYLAR sheets were first impressed along diagonal lines with a razor blade and then cut by an x-shaped cutter actuated by a spring mechanism.

Figures 2b and 2c show some details of the test section (open and closed). The overall length of the test section containing the nozzle and the diffuser blocks is 24 in. Twelve inches of this overall length is taken up by the nozzle, leaving another 12 in for various supersonic diffusers. The nozzle throat (0.472 x 2.00) in^2 is located at 4 in from the nozzle inlet. The nozzle exit area is (2 x 2) in^2. The supersonic nozzle contour was machined based on coordinates obtained from calculations using the method of characteristics for a uniform $M = 3$ flow at the exit. No boundary layer corrections were applied since no fixed design Reynolds number was used. The identical supersonic nozzle was used on a smaller scale in the previous investigations in the continuous tunnel.

As seen from Fig. 2c, the test section provides space and prepared feedthroughs above and below the nozzle and diffuser blocks. This arrangement was added for future experiments using boundary layer blowing or suction. The plexiglass windows allow visual observation of the entire nozzle and diffuser flow area (see Figs. 2b, 2c). The optical quality of the plastic windows is poor yet qualitative schlieren observations are possible. For pressure measurements to be performed along the flow, one plexiglass window is replaced by a metal sidewall providing holes at many locations to install pressure transducers. In Figs. 2b and 2c this metal plate is seen at the back wall of the test section. The pressure measurements were made using Kistler piezo quartz pressure transducers, Model 606L, which were mounted along the centerline of the side wall with their membrane flush to the channel wall.

The experimental set-up for high speed movies is shown in Fig. 1a. Using two 9½ in diameter parabolic mirrors, a 9½ in long section of the nozzle and/or diffuser could be observed in one experiment. The camera used was a 16 mm Fastax WF3 with a maximum framing rate of 5000 frames per second. The Ludwieg tube and the camera were triggered manually, whereas the storage oscilloscope, Tektronix Model 5103N, capable of recording four pressure signals simultaneously, was triggered by breaking a circuit when releasing the pin to rupture the diaphragm. For the experiments performed with the upstream diaphragm, the output of the first pressure transducer located either 1 or 2 in from the nozzle entrance was also used to trigger the oscilloscope.

Dry air from bottles (Dew point of 213°K max) was used as the test

gas in all the experiments. All tests were performed with an initial upstream pressure of p_4 = 700 torr, resulting in a supply pressure of p_3 = 675 torr in the first flow cycle of the Ludwieg tube. In all experiments the initial temperature in the tube was constant and equal to T_4 = 296°K, resulting in a supply temperature T_3 of 293°K. The subscript 3 refers here to the state parameters after the expansion fan has passed into the supply tube. Since in our Ludwieg tube the steady flow speed in the nozzle supply after passage of the expansion is very low, i.e. $M_3 = 0.02$, $p_3 \cong p_o$ and $T_3 \cong T_o$, where p_o and T_o are the supply pressure and temperature of the nozzle during the first flow cycle.

B. TYPICAL RESULTS AND DEFINITIONS

Figures 3a, 3b, 3c depict typical traces of static pressure as a function of time taken at the nozzle exit (x = o) center for the nozzle followed by a 6 in diffuser. An upstream supply pressure, p_o, of 675 torr, a supply temperature (T_o) of 293°K, and a downstream pressure (p_1) of around 30 torr applies. Figures 3a and 3b were representative of experiments conducted with a downstream diaphragm, while Fig. 3c was obtained with an upstream diaphragm. In Figs. 3a and 3b the oscilloscope was triggered by breaking a circuit when the pin was released to rupture the diaphragm. In Fig. 3c the triggering of the oscilloscope was accomplished by the output of a pressure transducer located at 1 in from the nozzle entrance (x = -11 in since x = o at nozzle exit), sensing the arrival of the shock wave-generated by the rupture of the upstream diaphragm. As observed from Figs. 3a and 3b for a downstream diaphragm,

the pressure trace starts from its initial value (700 torr), it then decreases with the arrival of the expansion wave and it levels off to its steady state fully developed supersonic flow value. At first a small pressure bump is seen which is known to be caused by the starting shock for such an experimental set up (Cagliostro, 1972; Smith and Mosnier, 1973). The time period from the arrival of the expansion wave to the attainment of the steady state pressure value is defined as the starting time (t_s)at a given location. When the dump tank was not connected to the downstream section of the Ludwieg tube, the steady state value of the pressure was observed to be terminated by an abrupt change of the pressure (Fig. 3a). This pressure increase is caused by the shock waves reflected from the downstream end of the tube (Fig. 1a). The time period between the start and the end of the steady state value of the pressure is defined as the running time. Connecting the dump tank to the downstream section of the tube reduced and eliminated the disturbances caused by the reflection of the shock waves (Fig. 3b).

The pressure trace of Fig. 3c, recorded with an upstream diaphragm, shows a sudden increase in the pressure level with the arrival of the shock wave generated by the rupture of the diaphragm. This rise is followed by a rapid decrease and a leveling off of the pressure to its steady state value, corresponding to the local pressure expected for a fully developed supersonic flow. The starting time in this case is defined as the time period starting with the arrival of the shock wave (start of pressure rise) and ending with the attainment of the steady state pressure level.

C. NOZZLE CALIBRATION

Results of a nozzle calibration are given in Fig. 4. The dashed line in the converging part of the nozzle was calculated from area ratios for one-dimensional isentropic flow. The solid line starting at the nozzle throat and extending to the diverging part of the nozzle was obtained from the calculation by the method of characteristics for the nozzle. Agreement between observed and theoretical pressure distribution is found to be good within the accuracy of the pressure measurement. The limit of this accuracy is given by the scale on the oscilloscope which must encompass all pressure values of interest in starting experiments. In Fig. 4, therefore, the points given represent average values from several measurements at one *single point*. From these static pressure measurements, the nozzle exit Mach number was found to be $M = 2.8$ ($\pm$ 0.2). This result was also verified by the Mach angle measurements at the nozzle exit obtained from the high speed schlieren motion pictures. Under the current conditions ($T_o = 293°K$, $p_o = 675$ torr) the Reynolds number at the nozzle exit is $Re_D = 3.6 \times 10^5$ and the boundary layer displacement parameter is of the order of $\delta^*/D \sim 0.04$. Thus, the flow parameters are within the range covered in the previous work (Merkli, 1975b, 1976).

III. RESULTS

A. *DOWNSTREAM DIAPHRAGM LOCATION*

1. Pressure at diffuser exit

If a Ludwieg tube diaphragm located downstream of the test section is ruptured, a complicated flow pattern develops until the steady state of the first cycle of Ludwieg tube operation is reached. Therefore, it is not obvious what diffuser back pressure, p_d, is reached for a given initial downstream pressure, p_1. Measurements of p_d as a function of p_1 were made for a 6 in long diffuser* (Fig. 5) without the dump tank being connected to the downstream end of the Ludwieg tube. The diffuser exit pressure, p_d, was measured on the centerline of the flow at 2 in from the diffuser exit (x = 8 in for the results shown in Fig. 5), but also in the separated flow region of the sudden increase in the area at the diffuser end (Fig. 2). Readings of the back pressure at both locations were close to each other. From Fig. 5 we see that for a 6 in long diffuser without the dump tank, the diffuser back pressure, p_d, changes linearly with the initial downstream pressure, p_1, once a certain low value of p_1 is exceeded.

2. First cycle flow termination

As mentioned earlier, without the dump tank connected to the downstream section of the Ludwieg tube and at high back pressures, the established nozzle-diffuser flow would sometimes not last throughout the whole first cycle (time required for the expansion to travel to the tube end and return to the test section). Clearly, this is possible only if in contrast to simple shock tube theory, the upstream and/or downstream

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*Diffuser length (see Nomenclature) is defined (e.g. Fig. 15) as the distance between the nozzle exit and the end of the diffuser.

conditions do not stay constant during the whole first cycle. To investigate this problem pressure measurements were made in the Ludwieg tube itself (no dump tank) at three different locations. There pressure gauges I, II and III were placed at 40 in upstream of the diaphragm location (x = -28 in), at 48 in downstream of the diaphragm location (x = 60 in) and at the end of the downstream tube respectively. As seen from the two x-t diagrams with the superimposed p-t measurements in Fig. 6 some reflections of the shock waves from the 90° bend T-piece of the tube (see Fig. 1a) are found to take place. This T-piece was installed in the tube to easily allow the use of other tube configuration, e.g. for the connections of the downstream side to the dump tank to increase the overall running time of the facility and to decrease the disturbances caused by the reflecting shock waves. Moreover a comparison of the pressure traces of Fig. 6a (high back pressure) and Fig. 6b (low back pressure) shows that for the low back pressures we find no clear indication of the presence of any shock waves as might be expected. The propagation speed of the weak compression waves in the downstream section of the Ludwieg tube changes appreciably with the pressure level. This indicates the need of a more detailed specification of the "first cycle" of the particular Ludwieg tube used.* In our case, the first steady flow period is terminated by either one of the following three causes: (i) Reflection of the expansion wave from the end of the upstream section (ideal situation), (ii) Reflection of the shock wave from the end of the downstream

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*Obviously no general interest is attached to the particular downstream configuration used here. However, similar problems may arise in other facilities to warrant this discussion.

tube section, (iii) Reflections of part of the shock wave from an intermediate downstream tube section. As seen from Fig. 7, the end of the first cycle is not always caused by the same effect. For $p_1 > 15$ torr, the reflection of the expansion wave from the upstream tube ends terminates the first flow cycle. This running time of the head of the expansion wave can be calculated and is constant in these experiments since the same upstream conditions prevailed in the experiments of Fig. 7. For $p_1 > 15$ torr the termination of the first cycle is given by partial reflections of the shock waves from the 90° bend T-piece in the downstream tube section as shown by the experimental curve of Fig. 7. The running time of the shock wave in the downstream tube section never terminates the first flow cycle but in general matches the running time of the expansion wave in the upstream tube section well, as is to be expected from the design of this particular Ludwieg tube. In the later experiments the driven downstream section was connected to a large dump tank having a volume of 17 ft^3 in order to avoid this problem. Pressure measurements similar to those presented in Fig. 6 no longer showed the pressure increases due to the reflection of the shock wave from the end flange of the T-piece, as recorded by the gauge situated downstream of the test section.

3. Starting time data

With our knowledge of the Ludwieg tube characteristics, we are now ready to evaluate the data of the diffuser experiments with a downstream diaphragm configuration. Figures 8 to 12 give the observed starting and total running times of the supersonic flow as defined before. The results

shown apply to both the flow at the nozzle end and at the diffuser end. They are given in the figures as a function of the initial downstream pressure, p_1, for the straight duct diffuser lengths L/D = 0, 1.5, 3, 4.5 and 6. Clearly, the starting time for the nozzle flow recorded with and without the dump tank, is independent of the initial downstream pressure, p_1 or pressure at the diffuser exit p_d, except when the diffuser is operated close to its performance limit depicted as the solid vertical lines. At this condition it is difficult to determine if the flow started at all due to the brief time scales involved. At the beginning of this critical performance limit, the flow at the nozzle exit appears to start properly, it then breaks down and starts again showing an unstable characteristic. As the back pressure is increased further, the breakdown of the supersonic flow at the nozzle exit becomes more obvious. It is ultimately accompanied by a steady local pressure increase which implies a slowing down of the flow velocity.

It is interesting to compare the total operating times (starting time and running time) with the different time limits of the facility as given in Fig. 7. If we compare one of the Figs. 8 to 12 with Fig. 7, we can determine why the flow breaks down by either a change of upstream pressure, a change of downstream pressure, or a weak shock wave reflection from the 90° bend T-piece. Figures 8 to 12 also show, that for low p_1, that is for correspondingly low p_d, supersonic flow prevails throughout the diffuser as expected. Here the diffuser simply acts as an extended test section of fixed cross section. For higher values of p_1 or p_d supersonic flow is not established at the diffuser end while it is

starting properly at the nozzle exit. Here the desired flow deceleration and pressure recovery take place in the diffuser.

Of primary interest to us, in fact the aim of this work, is the determination of the period of time required to establish flow at the nozzle exit. The starting times at the nozzle exit as defined previously have been summarized together with the starting times at the diffuser exit in Fig. 13. They are given as a function of the diffuser length. The recorded pressure signals in Fig. 14 moreover show details of the starting process at the nozzle exit with and without a diffuser. In Fig. 13 the starting time of supersonic flow at the nozzle exit for sufficiently low back pressure and straight diffusers is seen to increase for longer diffusers. The starting time at the diffuser exit shows a similar tendency but it increases at a higher rate as the diffuser length is increased.

Figure 15 depicts the dimensionless starting time distribution as a function of the dimensionless axial distance (x/D) from the exit of the nozzle for the nozzle and straight duct diffusers with different lengths. The dimensionless starting time ($\bar{t}_s$) for each location is defined as the starting time (t_s) divided by a characteristic flow time (τ_f) in the nozzle,

$$\bar{t}_s = \frac{t_s}{\tau_f}$$

This characteristic flow time, τ_f (Wegener and Cagliostro, 1972) is defined by

$$\tau_f = \frac{\ell}{a^*} ,$$

where a* is the speed of sound at the throat under critical conditions (M=1) given by $a^* = [2/(\gamma + 1)]^{\frac{1}{2}} \cdot (\gamma R T_o)^{\frac{1}{2}}$, and $\ell = \sqrt{R^* h^*}$. Here h* is height of the nozzle at the throat and R* is the radius of curvature of the nozzle at the throat. The characteristic length, ℓ, is directly related to the rate of flow speed increase in a given nozzle. For the specific converging-diverging nozzle used in the present experiments $h^* = 0.472$ in, $R^* = 7.64$ in, providing a value of $\tau_f = 0.153$ ms for the characteristic flow time for $T_o = 293°K$. The starting times upstream of the throat do not depend upon the diffuser length added to the nozzle. In the diverging section of the nozzle, downstream the throat, the starting times increase steadily at downstream locations for a given diffuser length and they are longer for the longer diffusers.

For a downstream diaphragm, the pressure traces at points located upstream of the throat, (see pressure trace of p-gauge II in Fig. 6) shows a decrease in the pressure level with the arrival of the expansion wave. The pressure level first undershoots and then it slightly overshoots its final steady state value for fully developed supersonic flow during the first flow cycle of the Ludwieg tube. Similar behavior was observed by previous investigators (Johnson and Cagliostro, 1971). In Fig. 15 we defined the starting time as the time interval between the arrival of the expansion wave and the first attainment of the steady state pressure value by ignoring the pressure variations prior to the final steady value. This fact shows that it is essential to carefully define starting times if comparison between different geometries are to be made.

B. UPSTREAM DIAPHRAGM LOCATION

After some modification of the Ludwieg tube an upstream diaphragm station was installed. Experiments similar to those reported above were performed in order to record the starting times of straight duct diffusers as a function of initial downstream pressure (p_1) and diffuser length (L). In all experiments conducted with the upstream diaphragm, the dump tank was connected to the downstream section of the Ludwieg tube.* A 0.003 in thick MYLAR sheet was now used as the diaphragm material. Before installation the MYLAR sheets were first scratched along diagonal lines with a razor blade. Operation was initiated by bursting the diaphragm with an x-shaped cutter actuated by a spring mechanism. The MYLAR diaphragm split along the previously marked lines without shattering into several pieces. However, it appeared that the breaking time of the diaphragm and the formation of the shock wave initiating the supersonic flow in the test section (Falk and Hertzberg, 1967) was not wholly reproducible. A variation of a few tenths of a millisecond arises and is noted in the scatter of the experimental results. Since starting times of the order of a few milliseconds are being measured with the upstream diaphragm configuration this uncertainty in the breaking time of the diaphragm becomes important.

Figures 16 to 20 present the measured starting times of the supersonic flow at the nozzle and diffuser end respectively as a function of

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*We recall that in this configuration the total operating time is dominated solely by the expansion fan travel.

the initial downstream pressure, p_1, for various straight duct diffusers of 0, 3, 6, 9 and 12 inches in length. With an upstream diaphragm the wave diagram of the Ludwieg tube starting process is simpler than the one for the downstream diaphragm (see Fig. 1b and 1c), and the flow is started readily by the shock wave moving through the converging-diverging nozzle and diffuser assembly. In turn much shorter starting times are expected and were reported in the literature (Falk and Hertzberg, 1967; Davis, 1968). As observed from Figs. 16 to 20, the starting times with an upstream diaphragm are indeed shorter than those observed with a downstream diaphragm for the same experimental conditions, i.e. identical nozzle-diffuser configurations and the same initial pressures. In Fig. 16, results are plotted for comparison with the previous data taken with the nozzle without diffuser. In all the experiments reported the nozzle entrance was located at 1.81 in downstream of the diaphragm. In Fig. 16, results obtained with the nozzle entrance located at 10.81 in downstream from the diaphragm location, did not show marked deviations in the starting times at the nozzle exit. The shock wave formed by the rupture of the diaphragm depends strongly on the initial pressure ratio. Since according to the simplified x-t diagram as presented in Fig. 1c, the starting times increases linearly with distance, they should be slightly longer for the case when the diaphragm is located at farther upstream of the nozzle entrance. The experimental results do not show this effect, however, we believe that this expected difference in the starting times is too small to be detected within the scatter of our experimental data. With the upstream diaphragm, the starting times of the nozzle and

diffuser exit flows are observed to increase steadily with the initial downstream pressure, p_1, i.e. for a decreasing overall pressure ratio. However, when the tube operation is close to the performance limit, the starting time increases sharply, the supersonic flow breaks down, and the pressure level starts increasing at the diffuser or nozzle exit.

Figure 21 finally presents the variation of the starting times of supersonic flow at the nozzle exit as a function of the diffuser length for various initial downstream pressures (p_1). For a given value of the initial downstream pressure, the starting time increases slightly for longer diffusers.

C. PRESSURE DATA

As the initial downstream pressure, p_1, was increased gradually for a given upstream supply pressure, p_o, and in a given nozzle diffuser configuration, the supersonic flow at the diffuser exit was observed to break down at a well defined initial downstream pressure. A sharp rise in the starting time and local pressure was associated with this situation. Continued increase in the initial downstream pressure above this limit, caused the local pressure at the diffuser exit to increase until it was almost equal to the initial downstream pressure (see Fig. 5). Although the increase of the initial downstream pressure, p_1, was accompanied by an increase in the starting time for the supersonic flow at the nozzle exit, no change in the local steady pressure or variation in the supersonic performance was observed. At a given higher value of the initial downstream pressure, the starting time for supersonic flow

at the nozzle exit was observed to increase sharply and the pressure at the same location, p_n, exhibited sharp jumps above its steady state operating value. This condition is caused by a disturbance of the supersonic flow at the nozzle end. This second limiting value of the initial downstream pressure, which allows undisturbed supersonic flow through the nozzle, divided by the upstream supply pressure, p_o, was recorded as the optimum pressure ratio. This optimum pressure ratio will start the supersonic nozzle flow and in the steady state it is followed by a steady local pressure increase in the diffuser implying a slowing down of the velocity or pressure recovery through the diffuser.

In Fig. 22, the maximum pressure ratios (p_1/p_0) which started the nozzle, are plotted as a function of the diffuser length for both the downstream and the upstream diaphragms. The results obtained with both configurations are observed to agree well with each other. The pressure ratio is found to increase with the diffuser length up to a value of L/D = 4.5. This value indicates the necessary optimum length for starting the supersonic nozzle flow under the prevailing flow parameters. This value is in good agreement with the previous work (Merkli, 1975a, b, 1976) which gave the necessary recovery length to be L/D $\sim$ 6 for the present situation in a continuous steady flow.

The inverse optimum pressure ratio to start the nozzle flow here is $p_o/p_1 = 5.2$. For the same experimental conditions, the breakdown pressure for a continuously operating nozzle-diffuser set-up was expected to be $p_o/p_d = 4.2$ (Merkli, 1975b, 1976). In the continuous wind tunnel experiments the breakdown pressure ratio was defined as the ratio of the

nozzle supply pressure divided by the maximum static pressure at the exit of the diffuser, when these conditions allow steady supersonic flow at the nozzle exit followed with a pressure recovery through the diffuser. The flow thus seems to require a starting pressure ratio across the nozzle-diffuser assembly which is about 1.2 times higher than the pressure ratio needed for steady continuous operation.

In Fig. 22, we have also plotted the pressure ratio (p_1/p_0) which causes the breakdown of the supersonic flow at the exit of the nozzle without a diffuser, or at the exit of the diffuser as a function of the dimensionless diffuser length (L/D). As observed from Fig. 22, the pressure ratio is constant, $p_1/p_0 = 0.1$ and it is independent of the diffuser length.

IV. CONCLUSIONS

An analysis of the obtained results brings us to the following conclusions:

1. The Ludwieg tube has proved to be a practical device for diffuser research.

2. Although the starting times for flow at the nozzle exit are much shorter for the upstream diaphragm location than for the downstream diaphragm configuration, they increase with the initial downstream pressure, p_1, and are longer for the longer diffusers.

For the downstream diaphragm location, the starting times for the flow at the nozzle exit are independent of the initial downstream pres-

sure, p_1, but still are longer for the longer diffusers.

3. The optimum initial pressure ratio, $p_o/p_1 = 5.2$, to start the flow at the nozzle exit was obtained for a diffuser length of $L/D = 4.5$. The flow at the nozzle exit required a starting initial pressure ratio, p_o/p_1, across the nozzle-diffuser assembly 1.2 times higher than the pressure ratio it can stand once in steady continuous operation.

4. The results obtained for the diffuser performance in a Ludwieg tube are in good agreement with the previous experiments conducted in a continuous wind tunnel.

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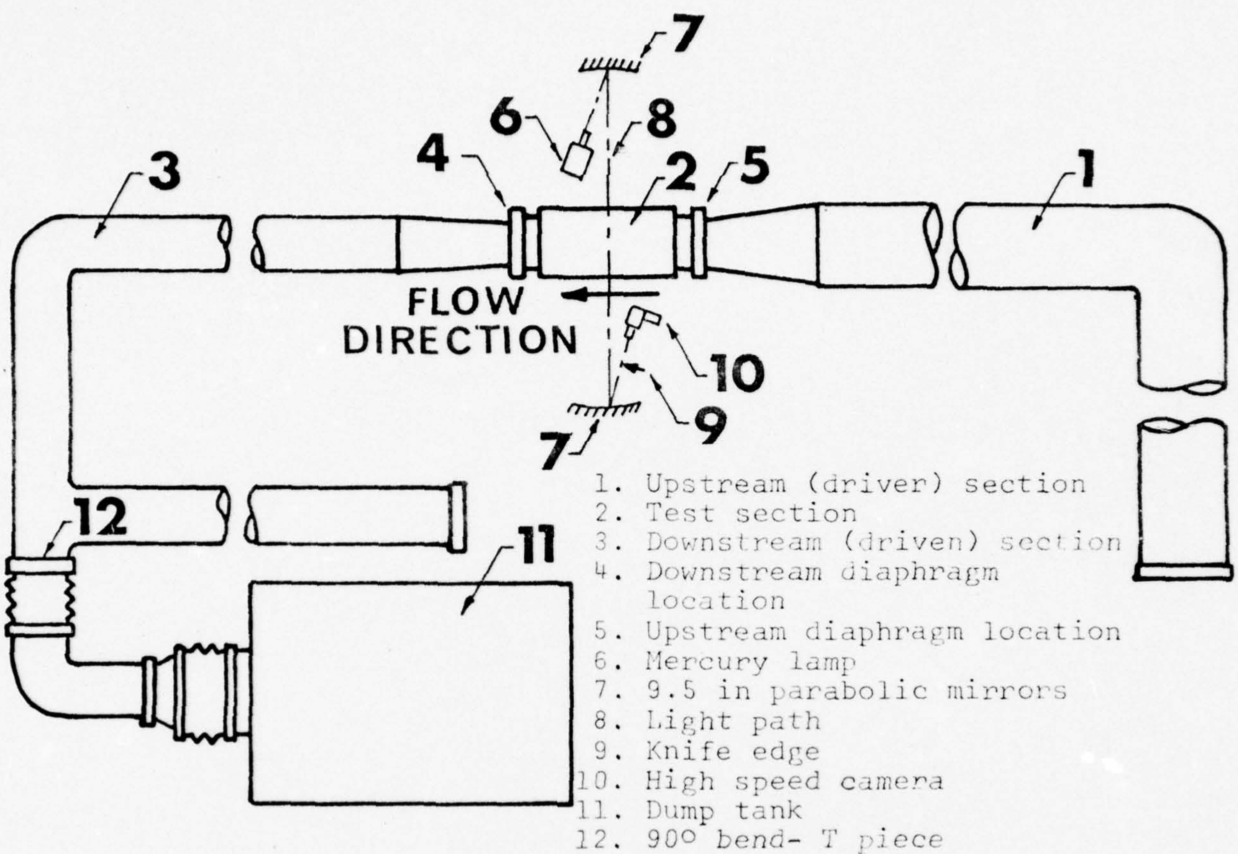
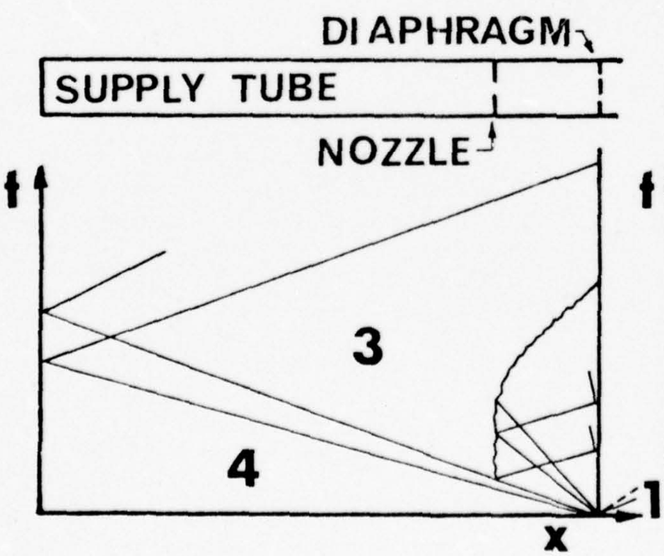


Figure 1a. The Ludwieg tube.



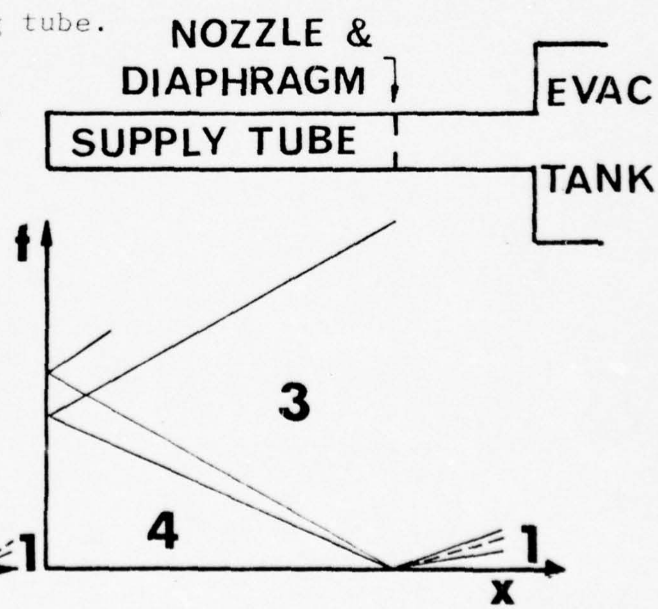


Figure 1b. Simplified x-t diagram for Ludwieg tube with downstream diaphragm location (Falk and Hertzberg, 1967). Diaphragm downstream of the nozzle.

Figure 1c. Simplified x-t diagram for Ludwieg tube with upstream diaphragm location (Falk and Hertzberg, 1967). Diaphragm located at the nozzle.

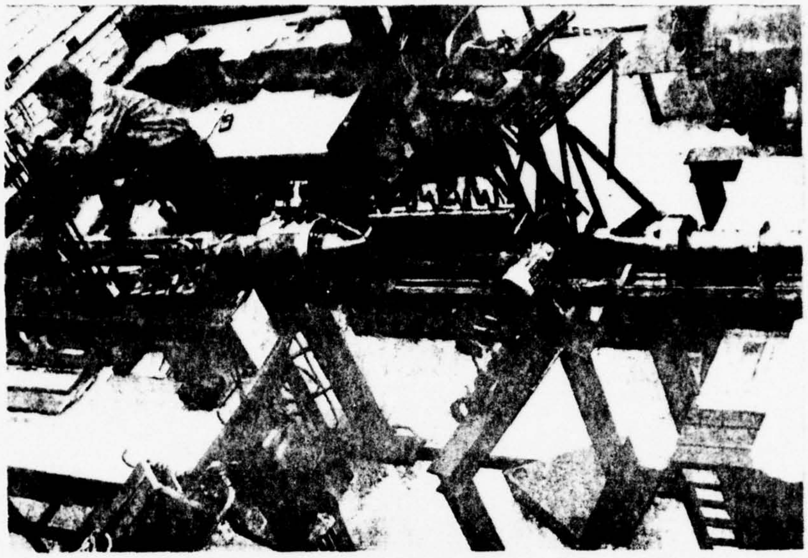


Figure 2a. Part of the Ludwieg tube. Test section open. Tube opened at downstream diaphragm location

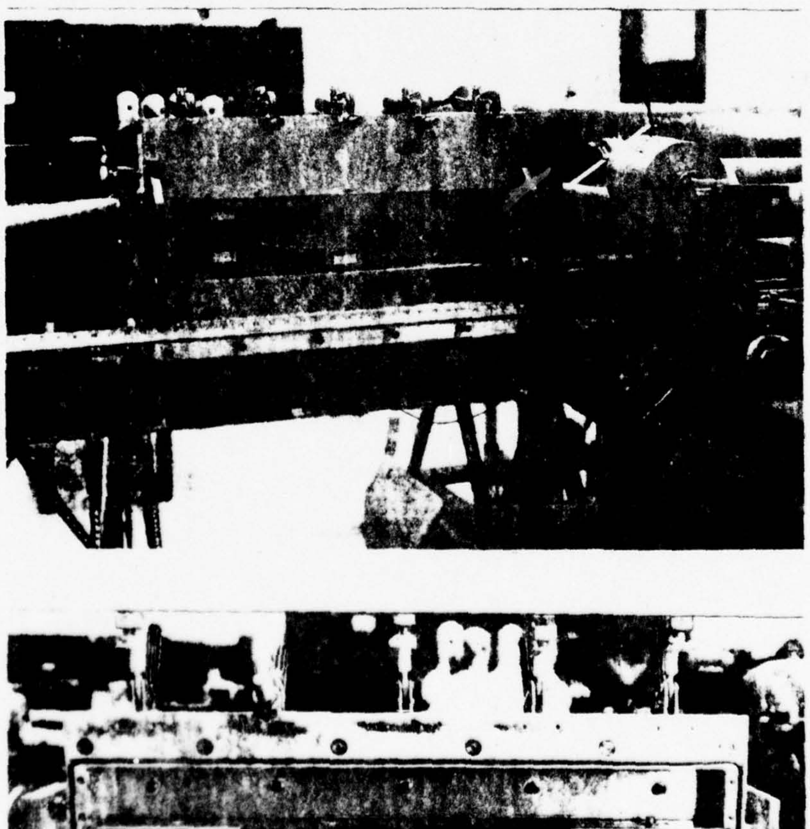


Figure 2b. The closed test section with metal wall containing holes for pressure transducers. Hg-arc lamp at right of test section.

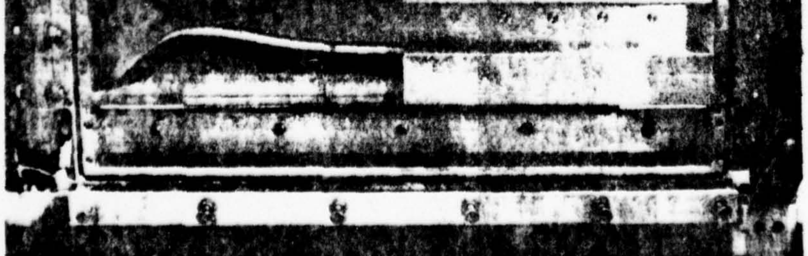


Figure 2c. The opened test section with nozzle and 12 in diffuser.

Figure 3a.
Downstream diaphragm
Dump tank not connected
$p_o = 675$ torr
$T_o = 293$ K
$p_1 = 39$ torr
$x = 0$ (nozzle exit)
Oscilloscope triggered by release of pin to rupture diaphragm.

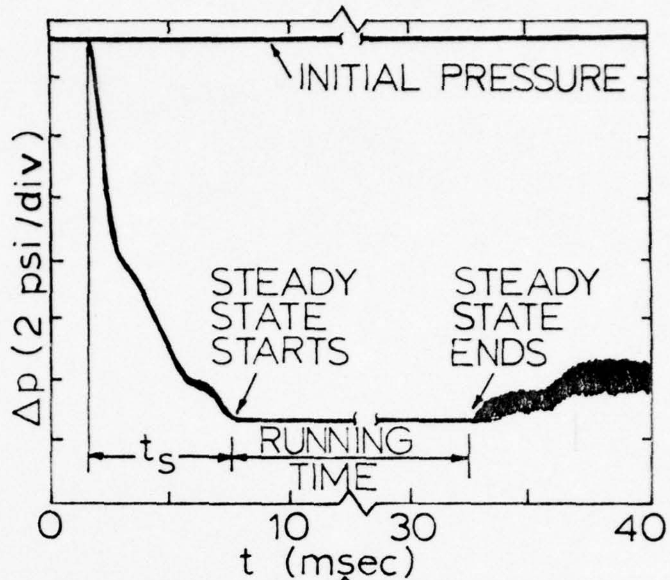


Figure 3b.
Downstream diaphragm
Dump tank connected
$p_o = 675$ torr
$T_o = 293$ K
$p_1 = 30$ torr
$x = 0$ (nozzle exit)
Oscilloscope triggered by release of pin to rupture diaphragm.

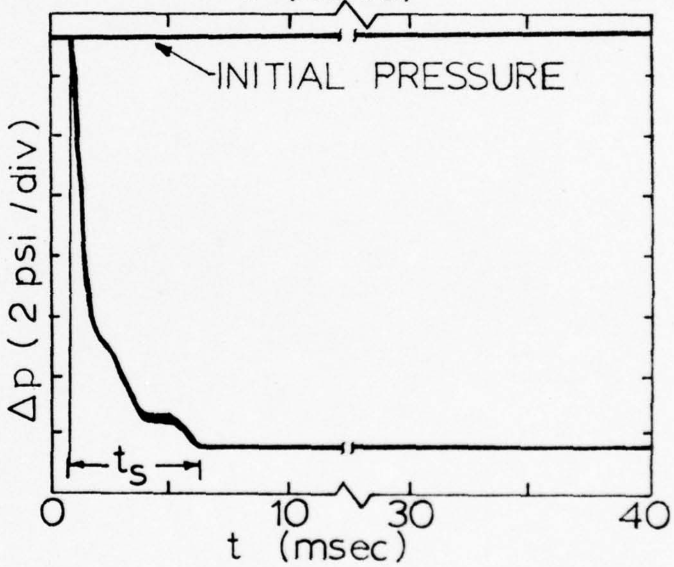


Figure 3c.
Upstream diaphragm
Dump tank connected
$p_o = 675$ torr
$T_o = 293$ K
$p_1 = 30$ torr
$x = 0$ (nozzle exit)
Oscilloscope triggered by output of pressure transducer located at 1 in from nozzle entrance (x= -11 in).

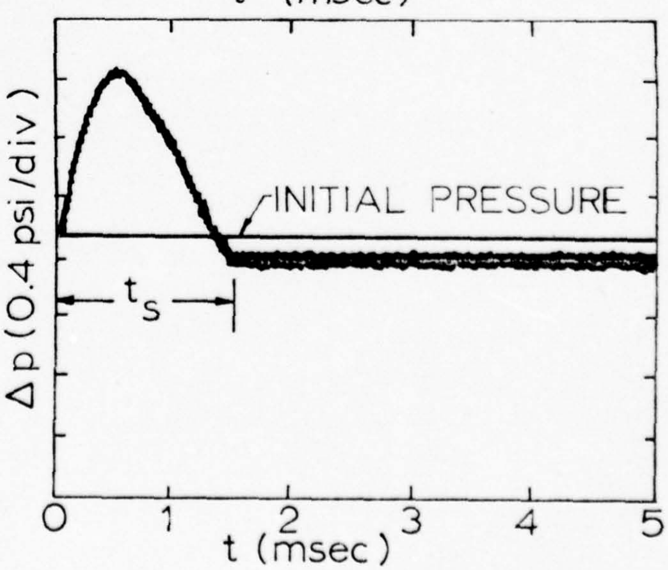


Figure 3. Typical traces of static pressure as a function of time and starting and running time measurements at the nozzle exit. Diffuser length, L/D=3. Note definition of starting time.

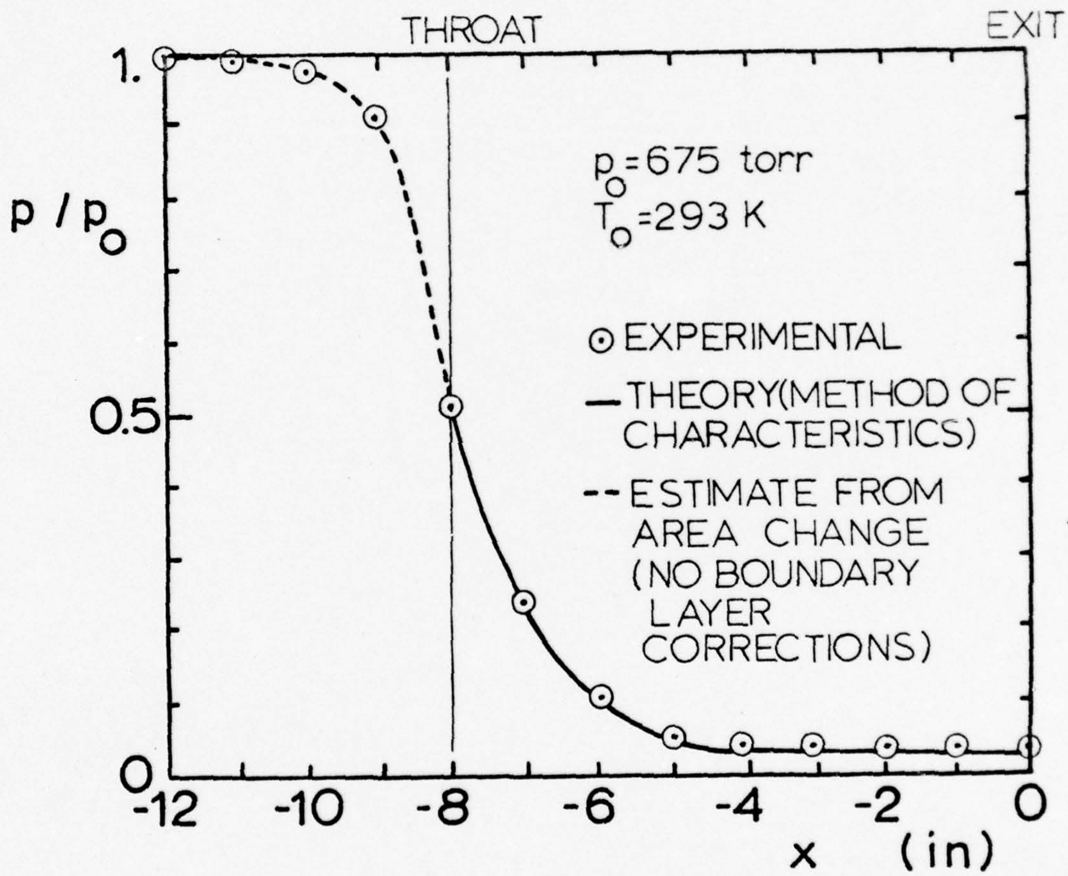


Figure 4. Static pressure distribution in the nozzle with a downstream diaphragm location and with and without the dump tank.

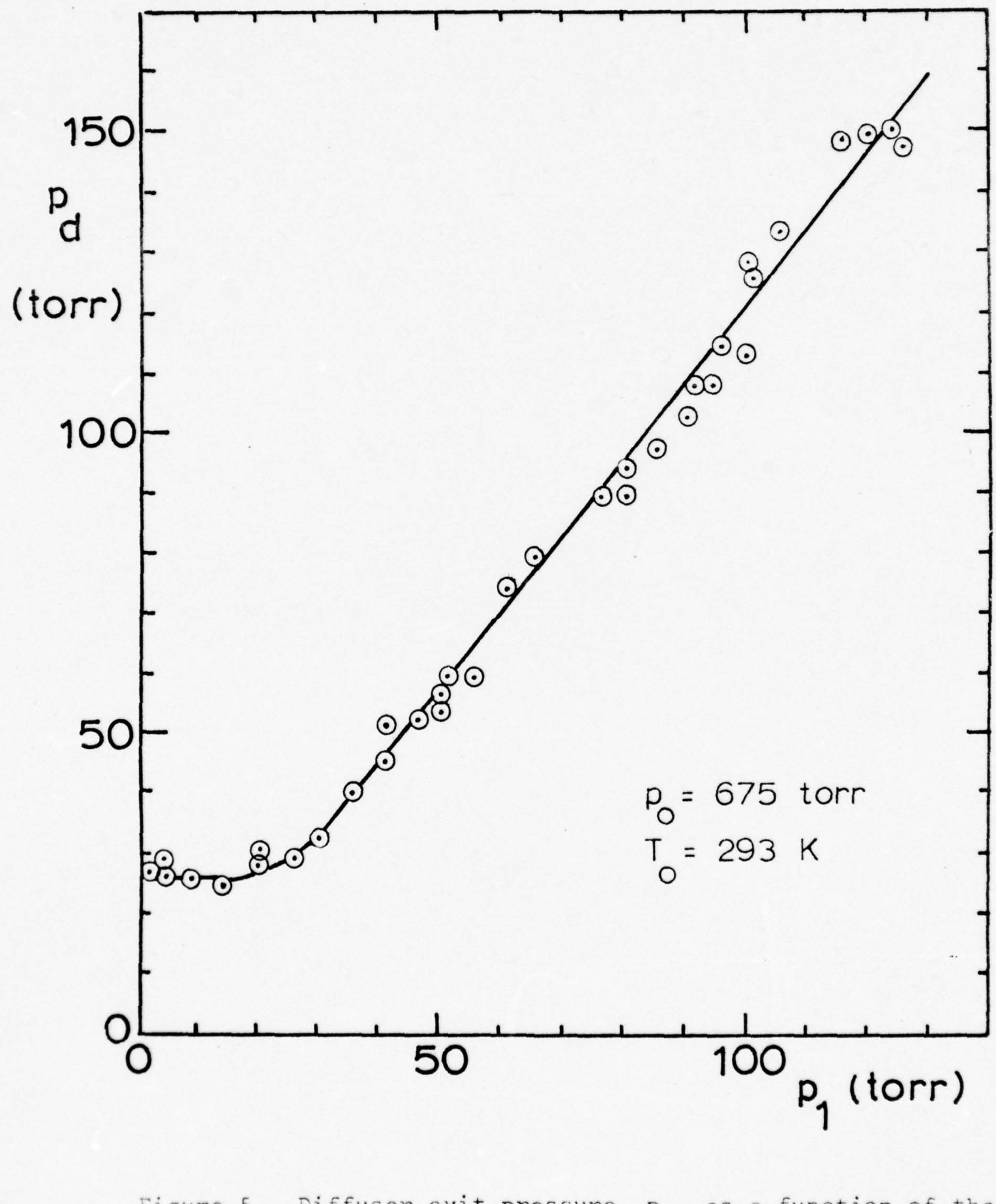


Figure 5. Diffuser exit pressure, p_d, as a function of the initial downstream pressure, p_1, for a 6 in diffuser with a downstream diaphragm location and without the dump tank.

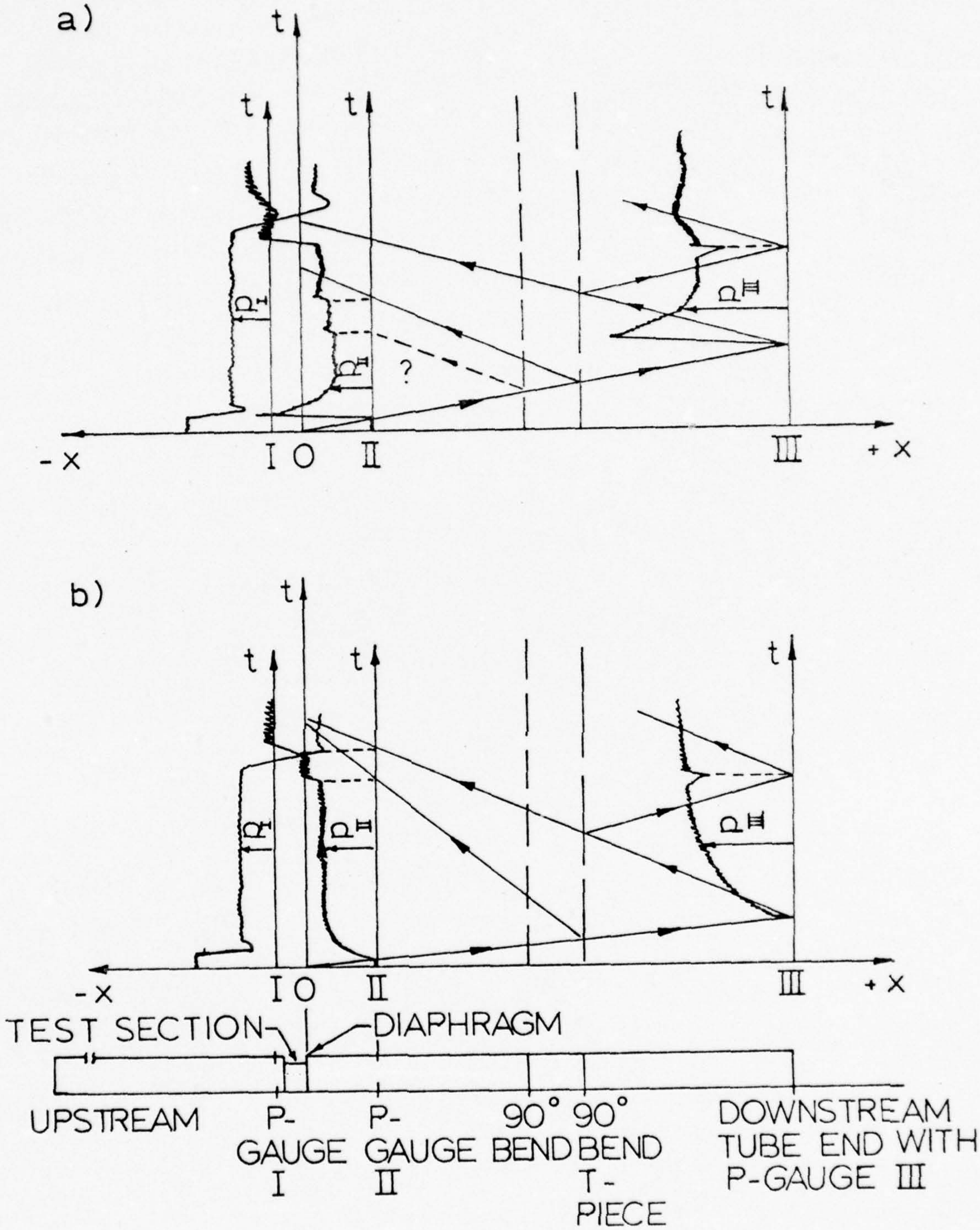


Figure 6. Reflection of shock waves in the Ludwieg tube, without the dump tank, shown as x-t diagrams for a downstream diaphragm location. p_0 = 675 torr, T_0 = 293 K.
a) p_1 = 75 torr b) p_1 = 2 torr.

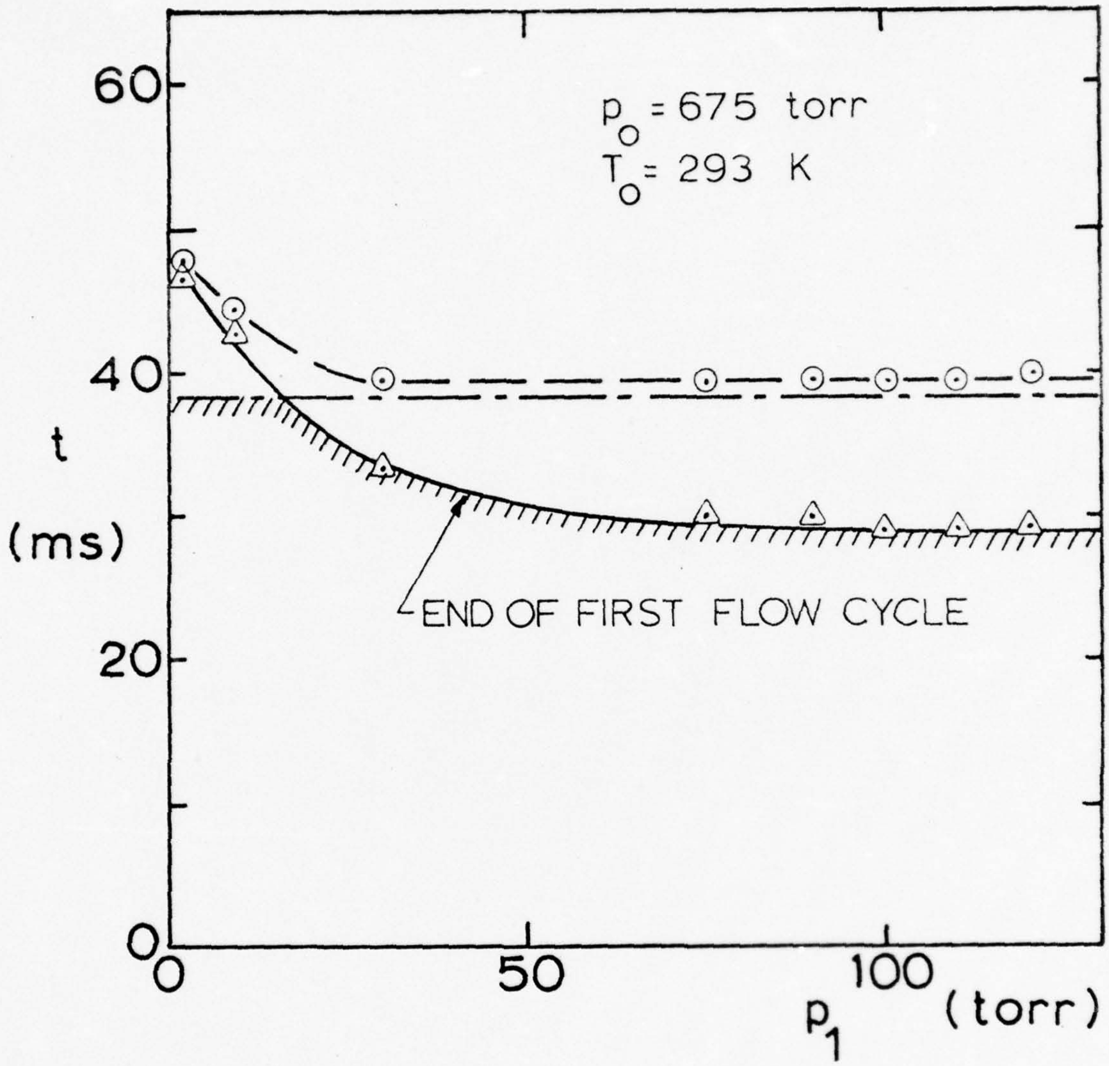


Figure 7. Experimental time limits for the first flow cycle of the initially used Ludwieg tube configuration (without dump tank, downstream diaphragm) as a function of the initial downstream pressure, p_1.

—·—— Calculated time until the reflection of the expansion wave from the upstream tube end (driver section, see Fig. 1) returns to the test section (T_o = 293 K)

—⊙— Experimental running time of the shock wave in the downstream tube section, to the tube end and back to test section.

—△— Experimental time at which part of the shock wave reflections from the 90°bend-T piece arrive at the test section.

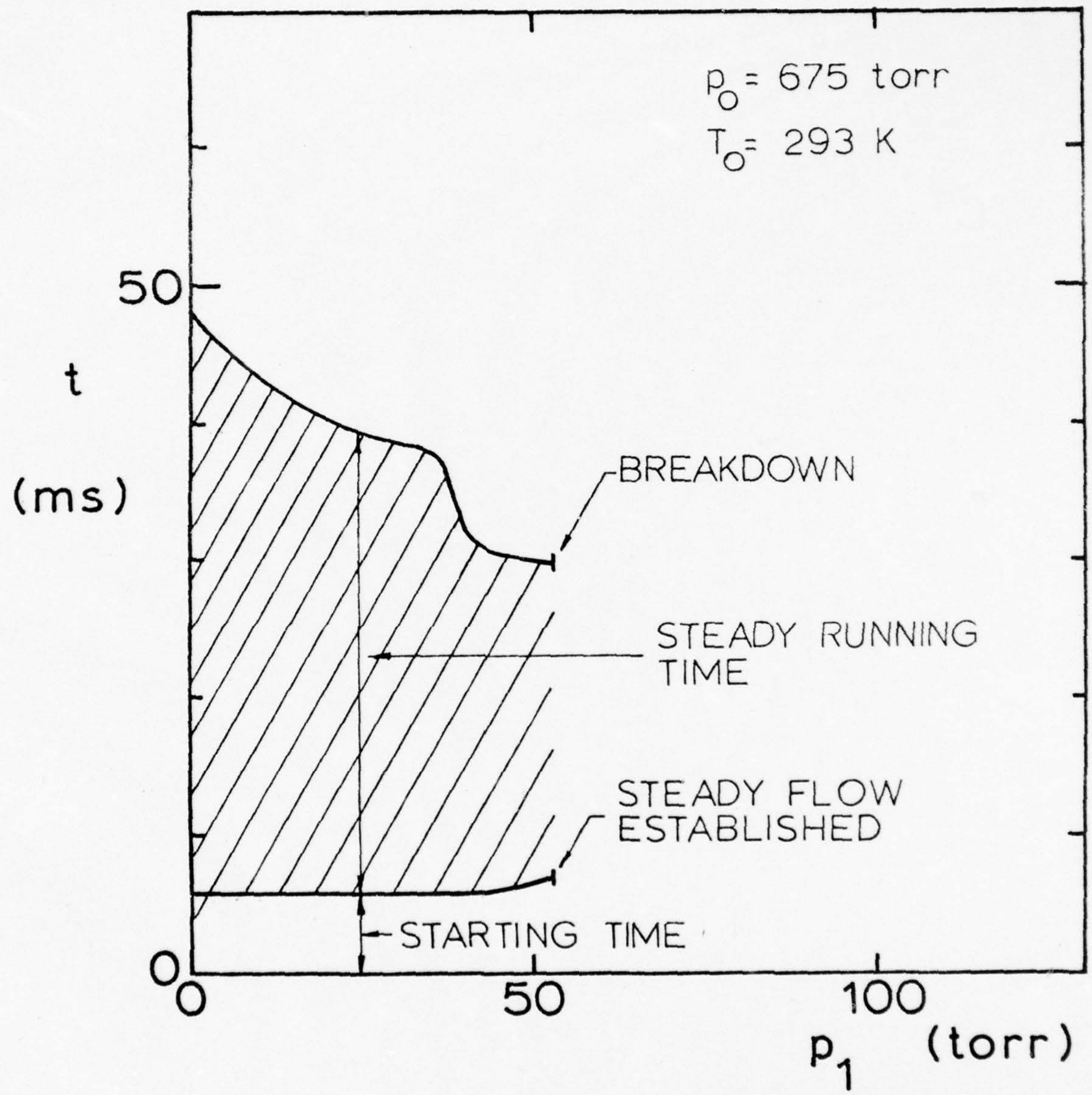


Figure 8. Starting and total running times for the flow at the nozzle exit without diffuser as a function of initial downstream pressure, p_1. Downstream diaphragm location.

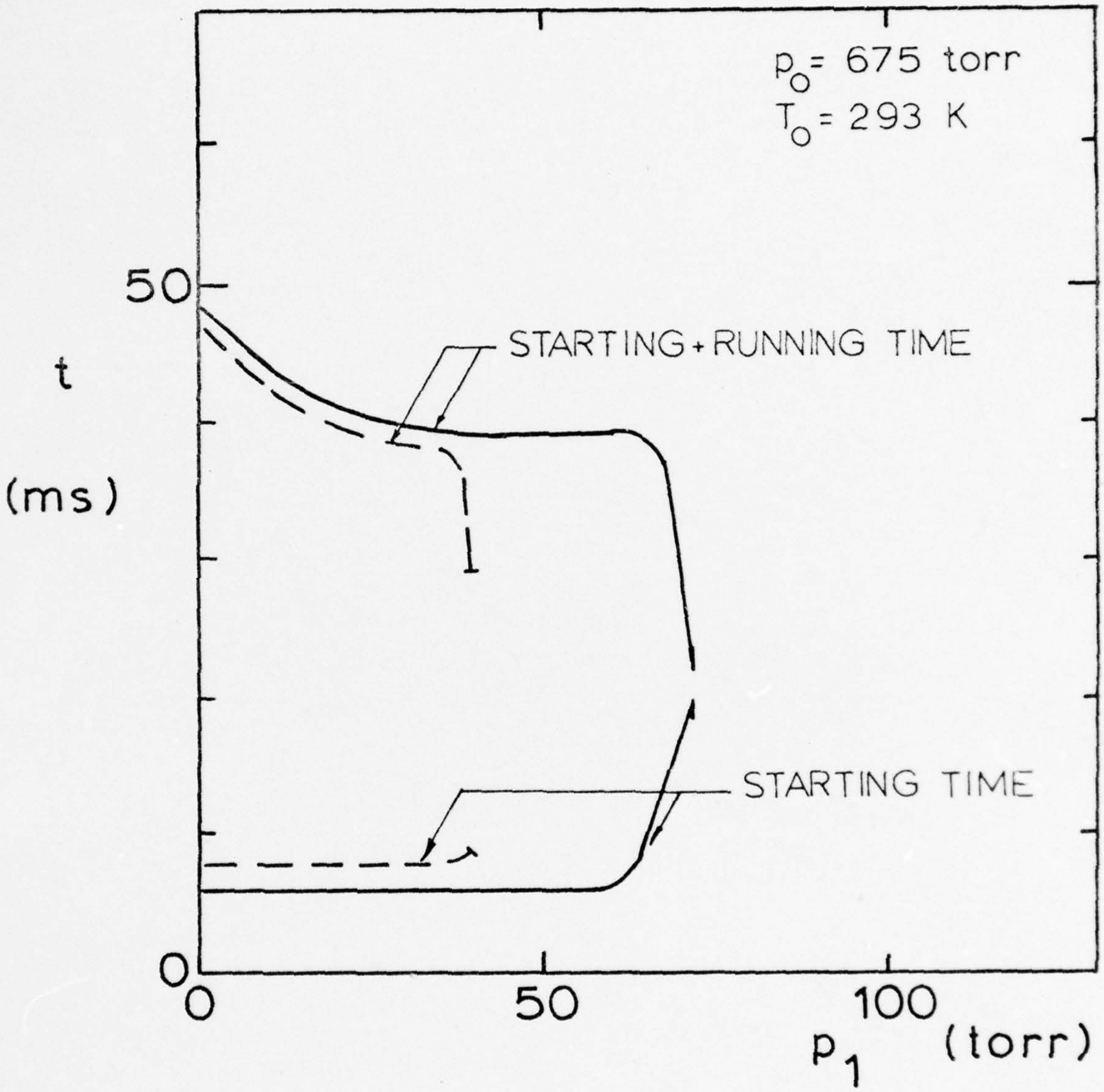


Figure 9. Starting and total running times for the flow at the nozzle and diffuser exits as a function of initial downstream pressure, p_1. Diffuser length, L/D = 1.5. Downstream diaphragm location.

——— Nozzle end

— — Diffuser end.

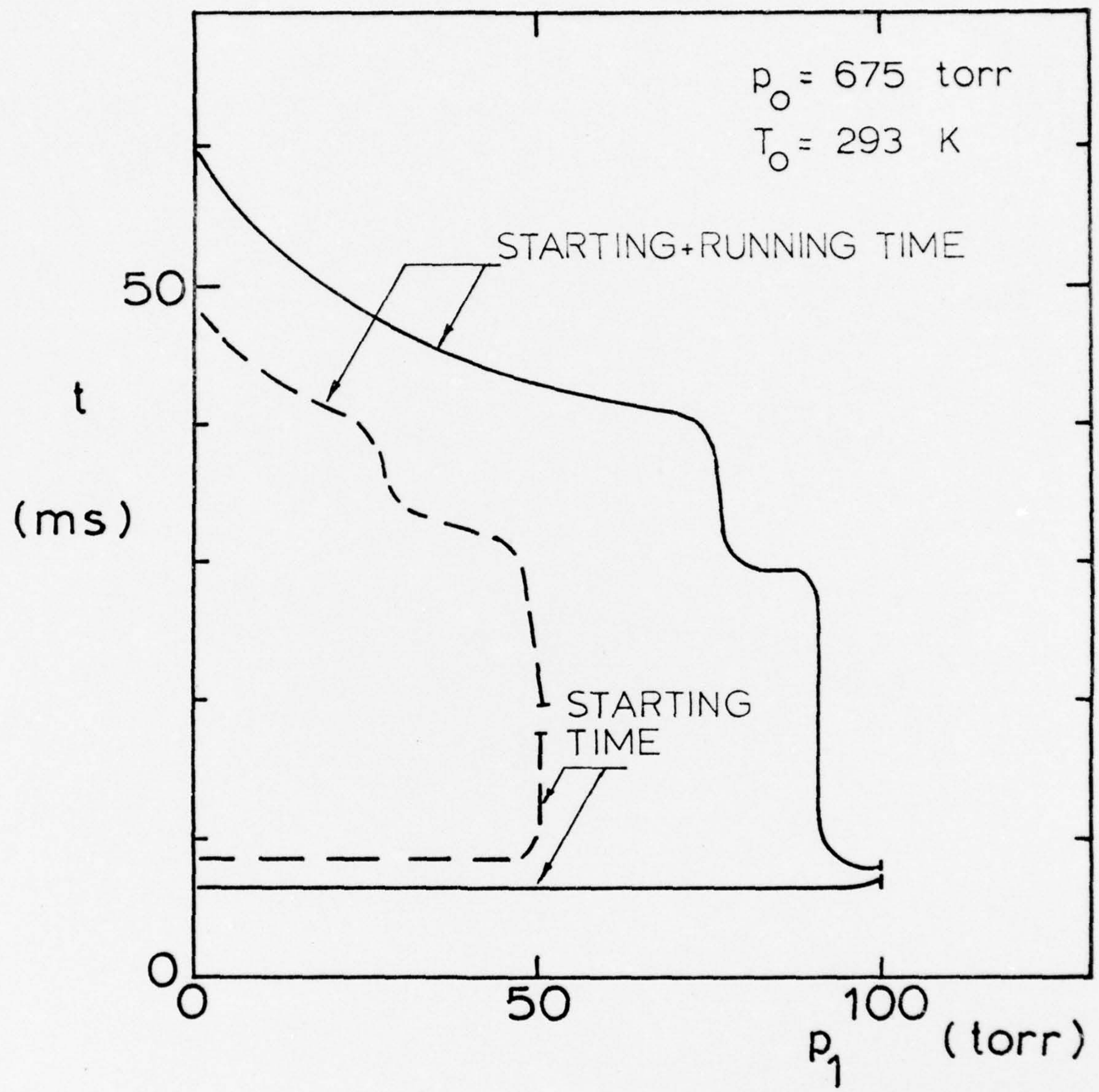


Figure 10. Starting and total running times for the flow at the nozzle and diffuser exits as a function of initial downstream pressure, p_1. Diffuser length, L/D = 3. Downstream diaphragm location.

——— Nozzle end

— — Diffuser end.

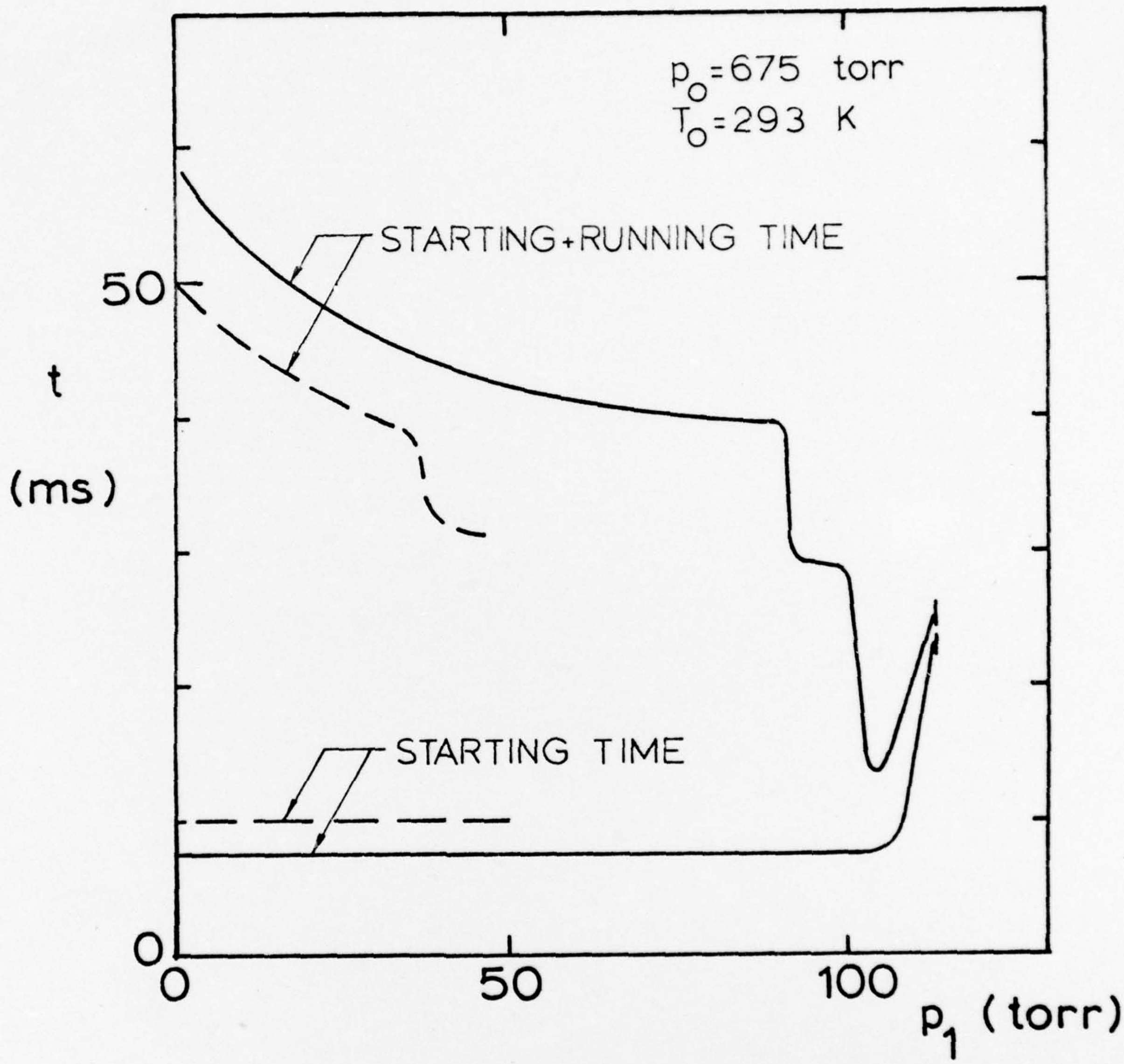


Figure 11. Starting and total running times for the flow at the nozzle and diffuser exits as a function of initial downstream pressure, p_1. Diffuser length, L/D = 4.5. Downstream diaphragm location.

——— Nozzle end

— — Diffuser end.

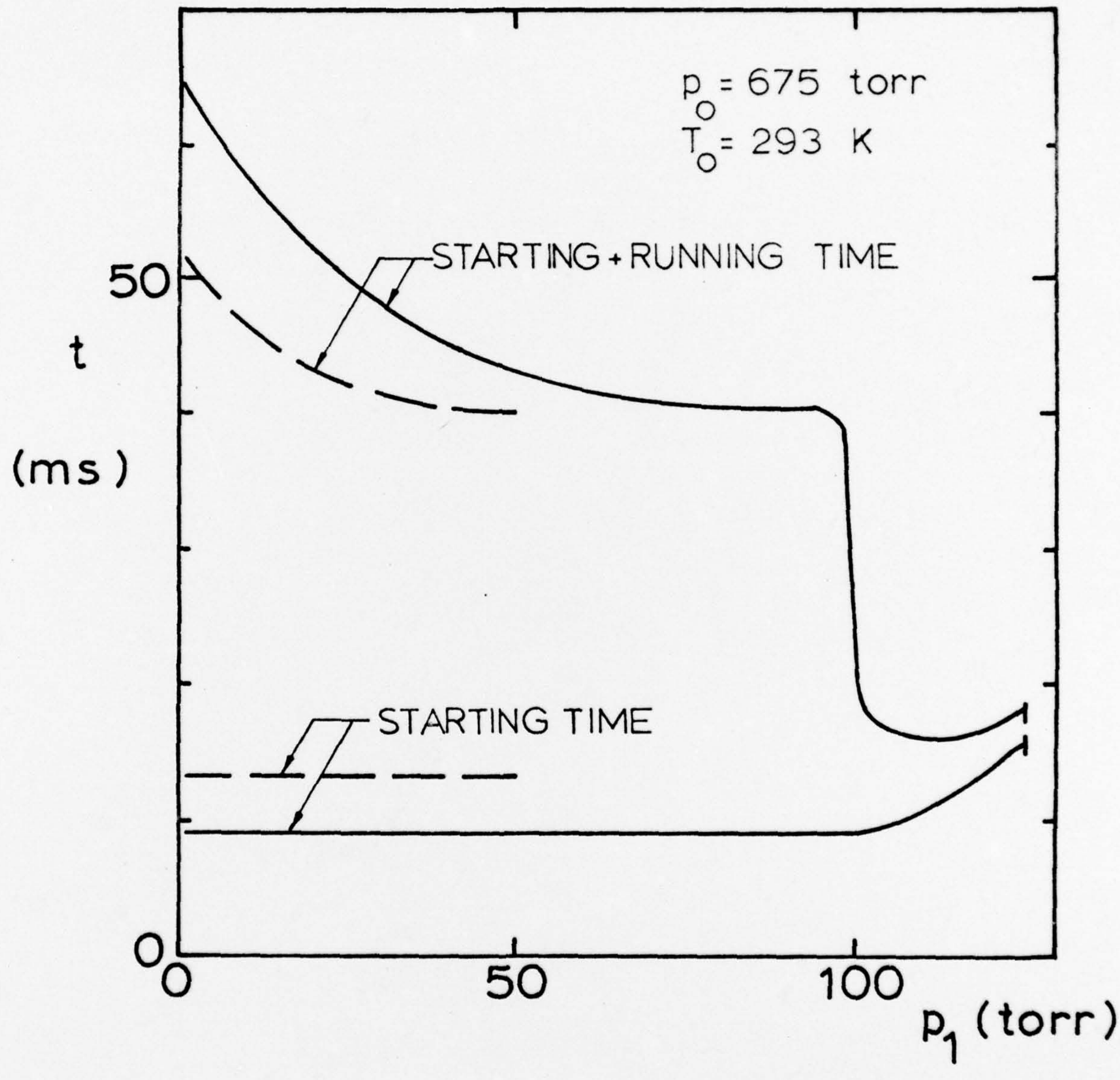


Figure 12. Starting and total running times for the flow at the nozzle and diffuser exits as a function of initial downstream pressure, p_1. Diffuser length, L/D = 6. Downstream diaphragm location.

——— Nozzle end

— — Diffuser end.

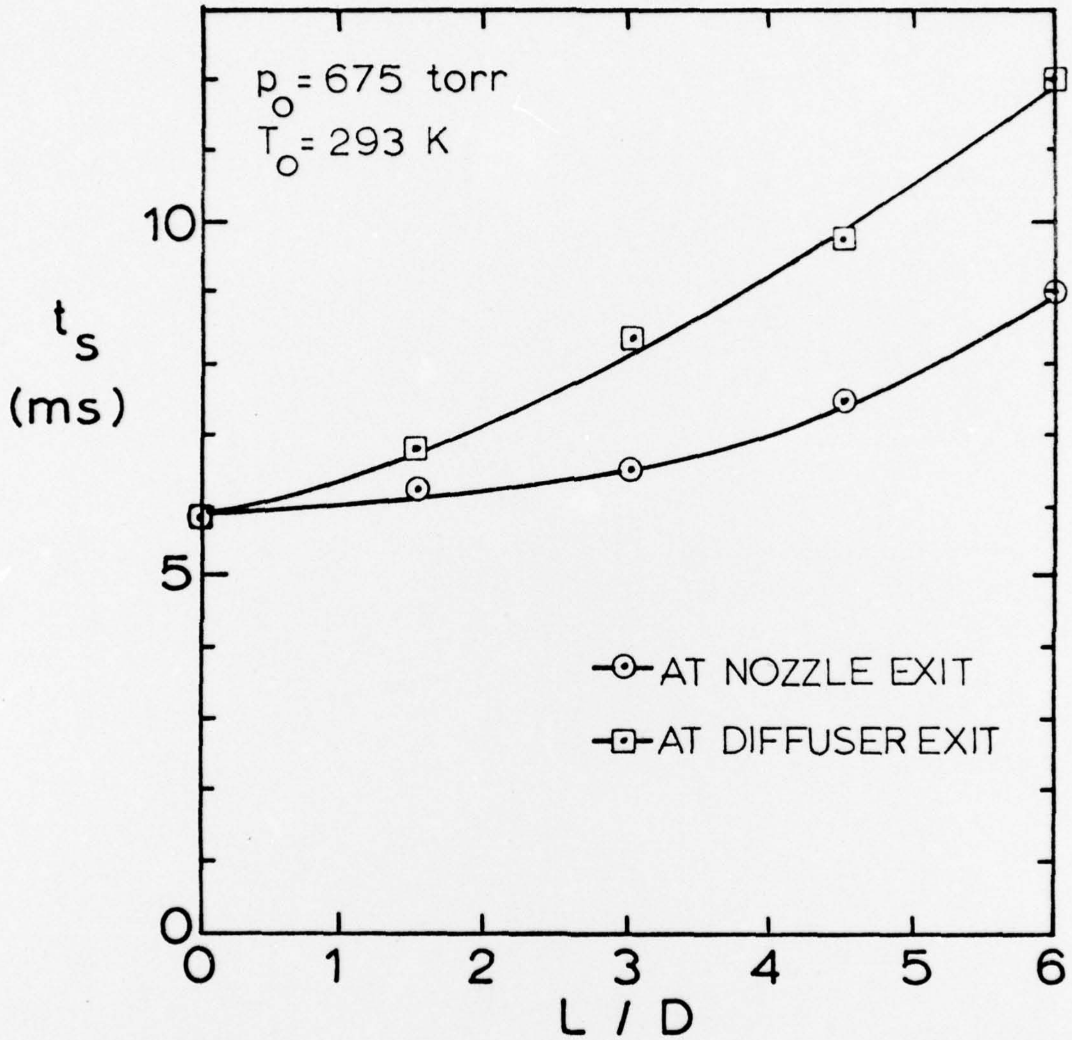


Figure 13. Starting times for supersonic flow at the nozzle exit and at the diffuser exit as a function of the diffuser length, L/D. p_1 is low enough to allow supersonic flow in the nozzle-diffuser section. Downstream diaphragm location.

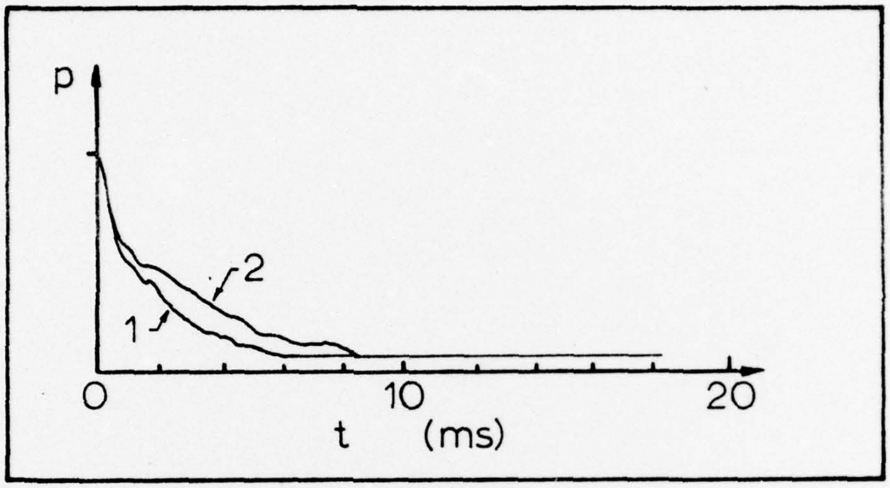


Figure 14. The pressure drop from initial conditions to the pressure of established supersonic flow at the nozzle exit as a function of time. Downstream diaphragm location.
P_0 = 675 torr, T_0 = 293°K.
1. Nozzle only, no diffuser.
2. Nozzle with L/D = 6 straight duct diffuser.

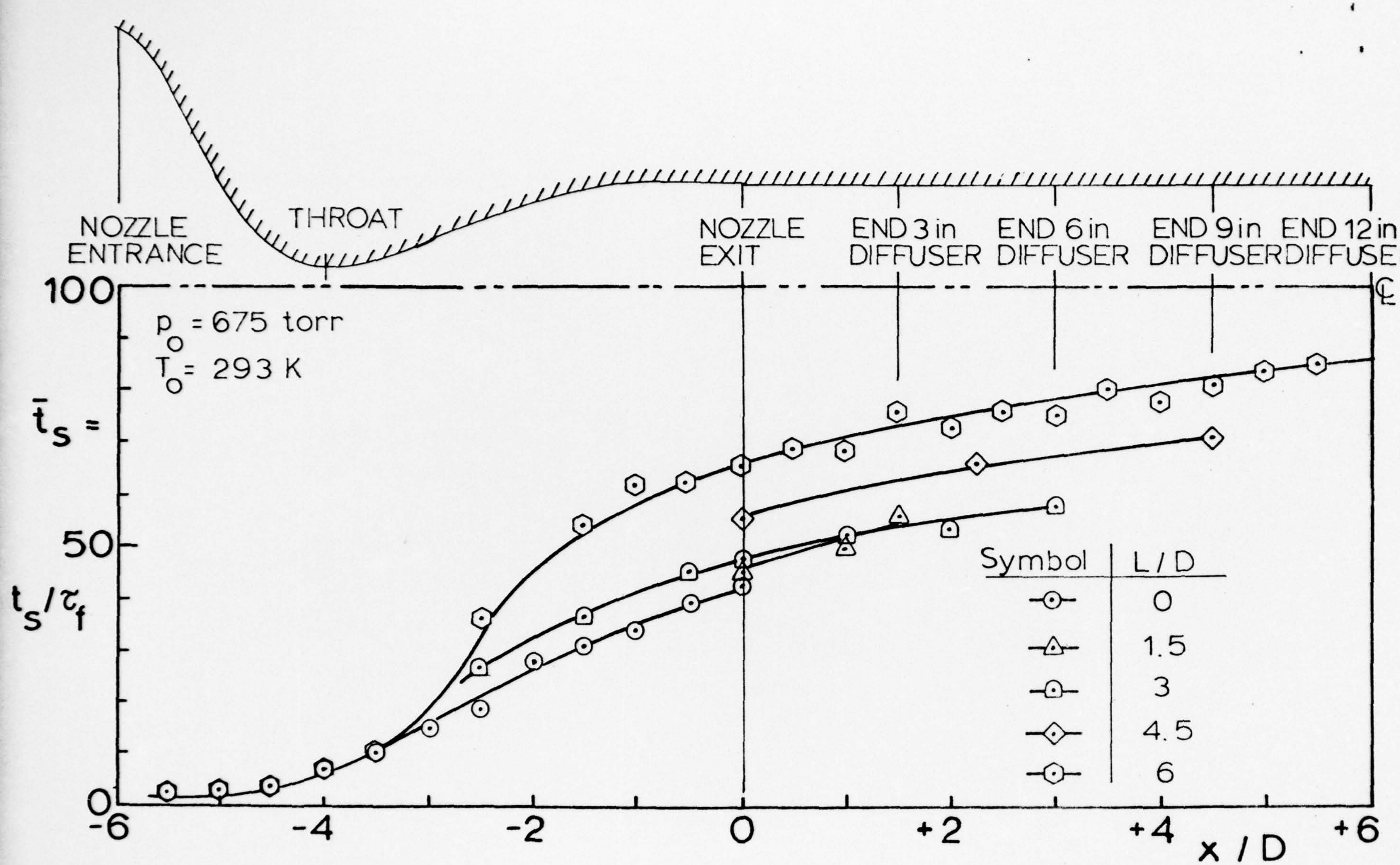


Figure 15. Dimensionless starting time ($\bar{t}_s = t_s/\tau_f$) as a function of dimensionless axial distance from the exit of the nozzle (x/D), for various diffuser lengths. Downstream diaphragm location. p_1 is low enough to allow supersonic flow in the nozzle-diffuser section.

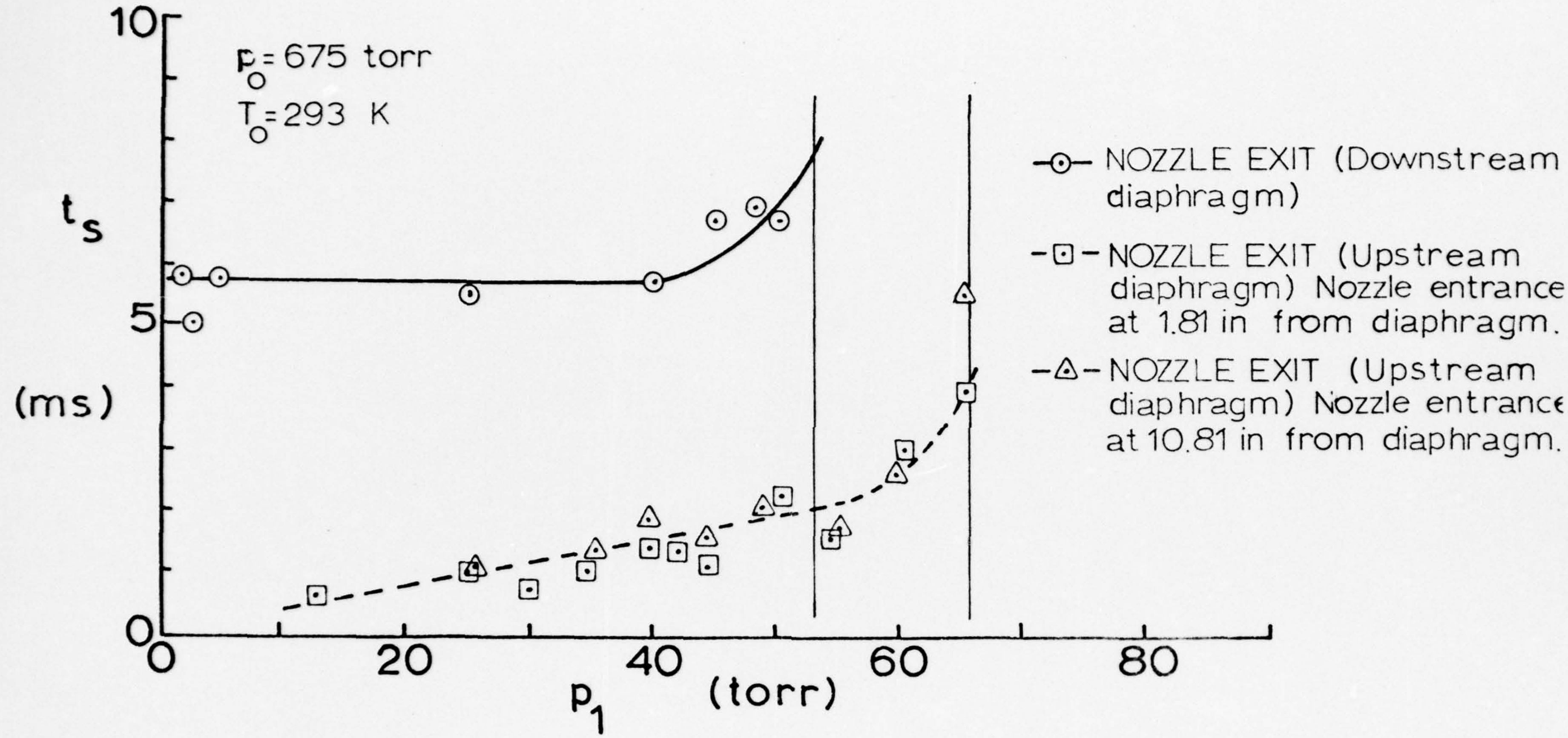


Figure 16. Starting times for the flow at the nozzle exit without diffuser as a function of initial downstream pressure, p_1. Upstream and downstream diaphragm locations. For the upstream diaphragm, two nozzle locations with nozzle entrance at 1.81 in and at 10.81 in from the diaphragm.

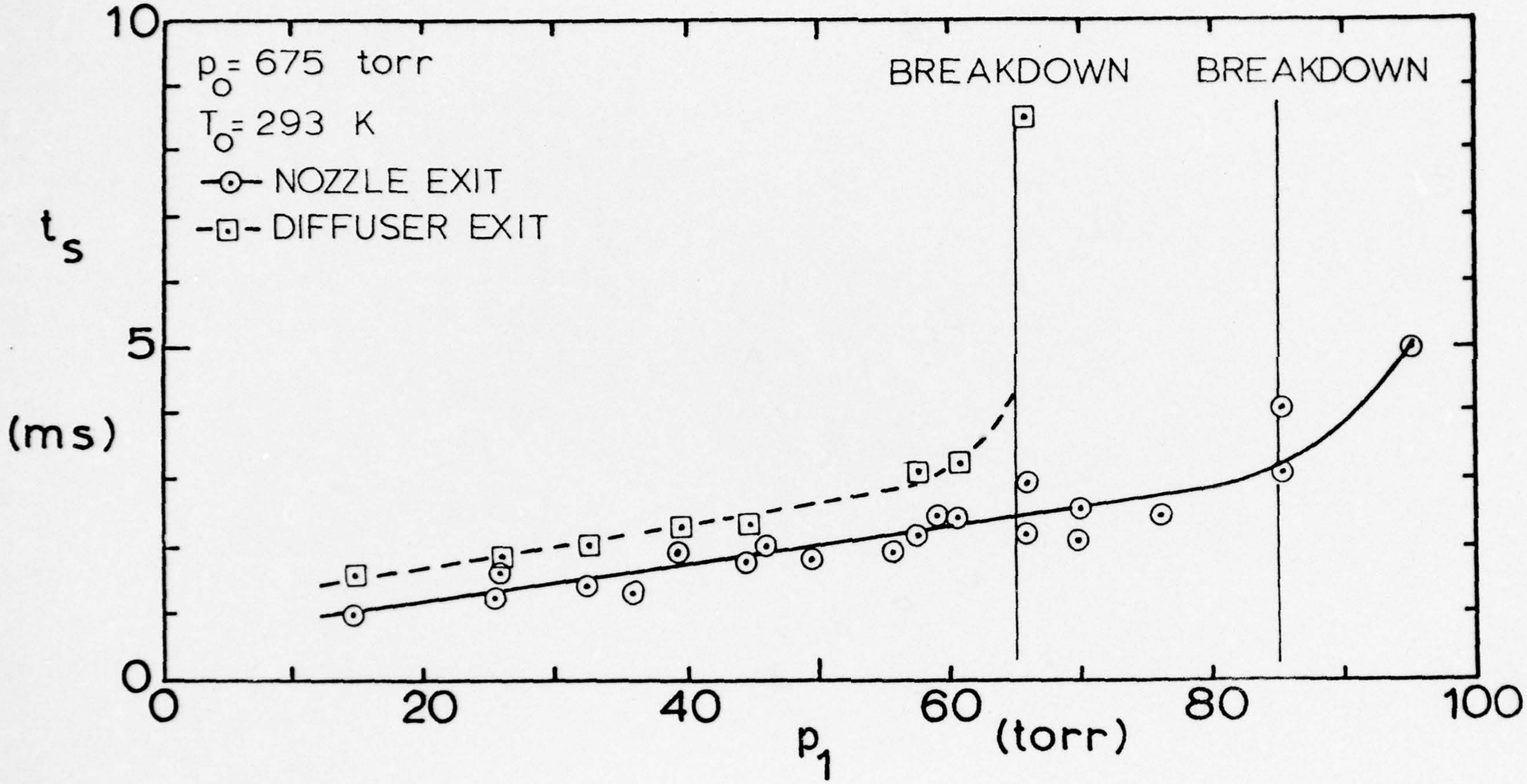


Figure 17. Starting times for the flow at the nozzle and diffuser exits as a function of initial downstream pressure, p_1. Diffuser length, L/D = 1.5. Upstream diaphragm location. Nozzle entrance at 1.81 in from diaphragm.

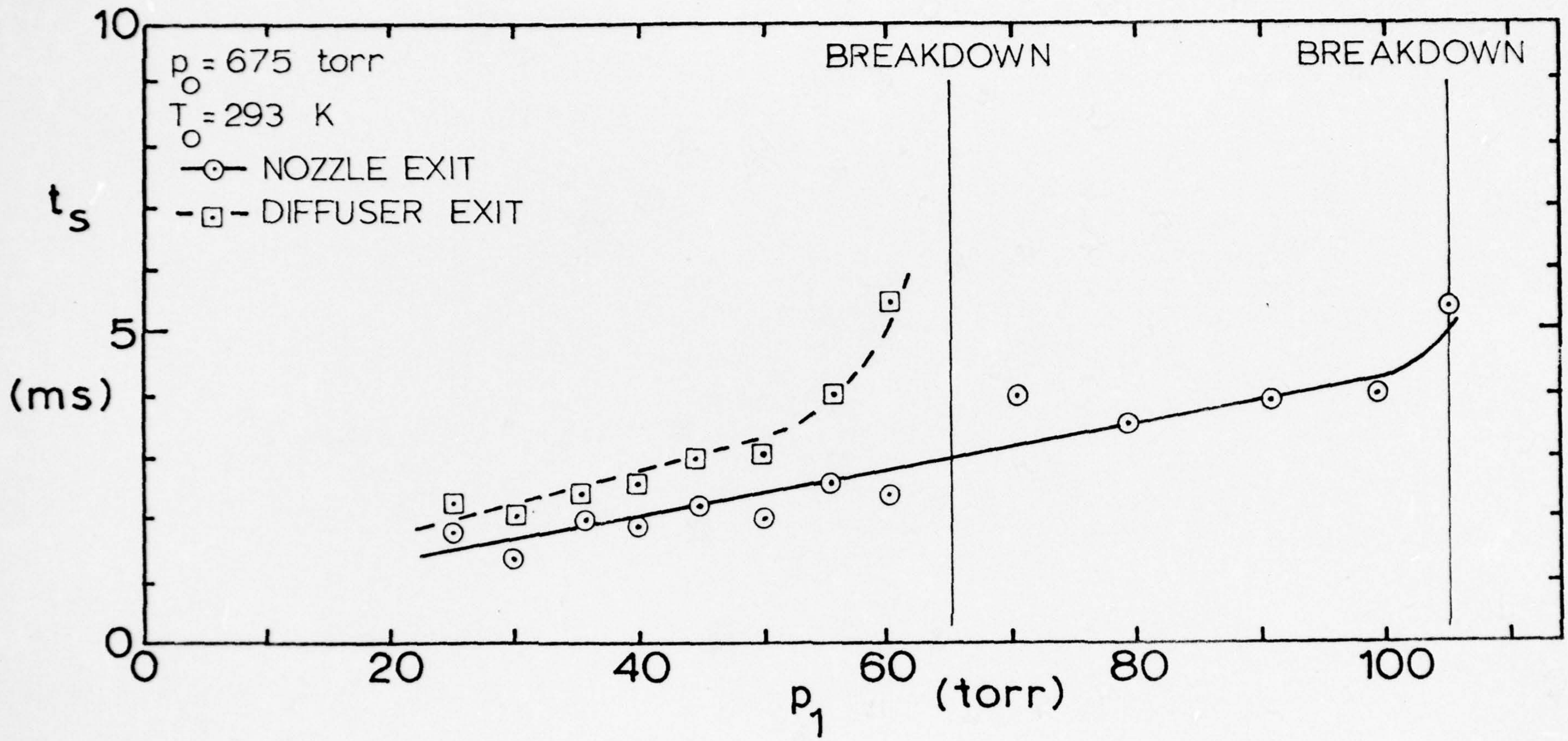


Figure 18. Starting times for the flow at the nozzle and diffuser exits as a function of initial downstream pressure, p_1. Diffuser length, L/D = 3. Upstream diaphragm location. Nozzle entrance at 1.81 in from diaphragm.

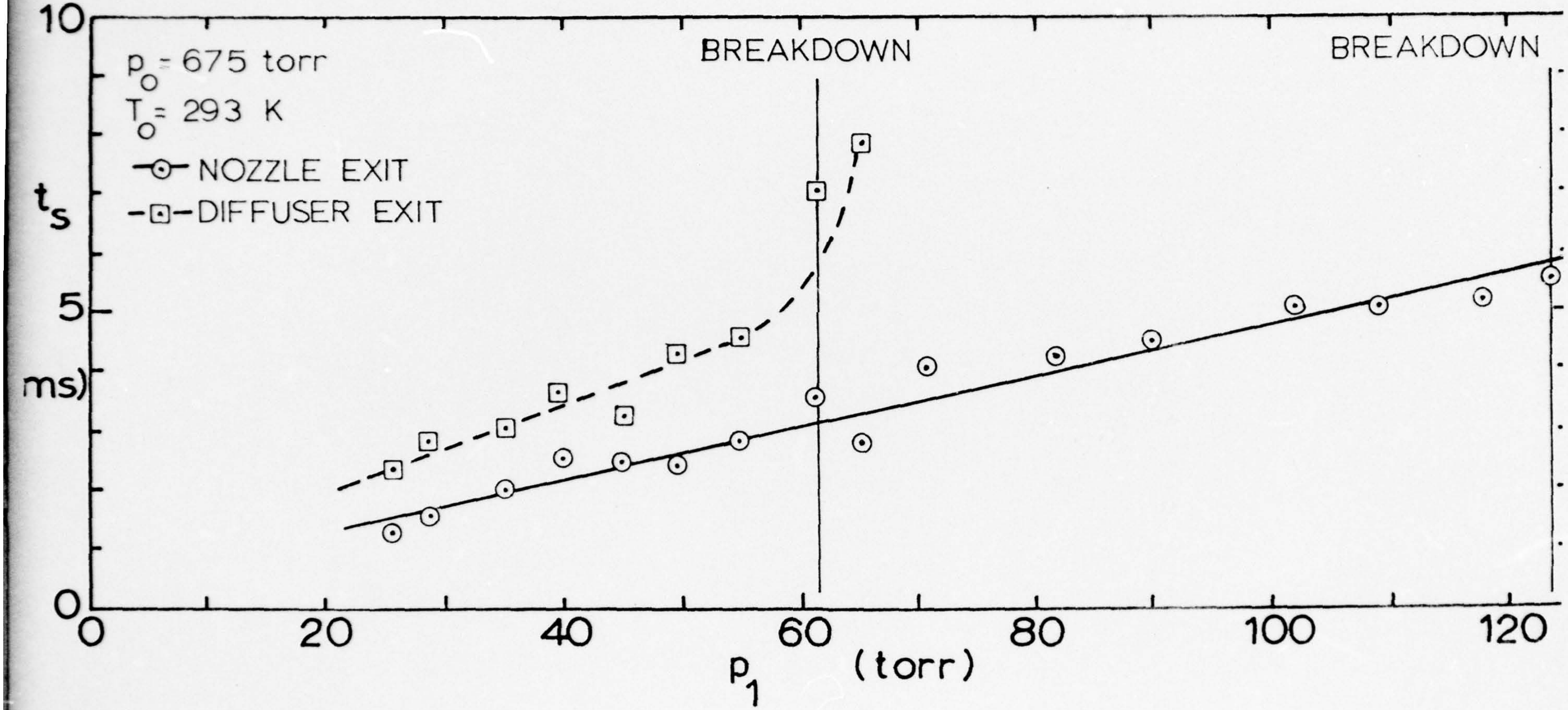


Figure 19. Starting times for the flow at the nozzle and diffuser exits as a function of initial downstream pressure, p_1. Diffuser length, L/D = 4.5. Upstream diaphragm location. Nozzle entrance at 1.81 in from diaphragm.

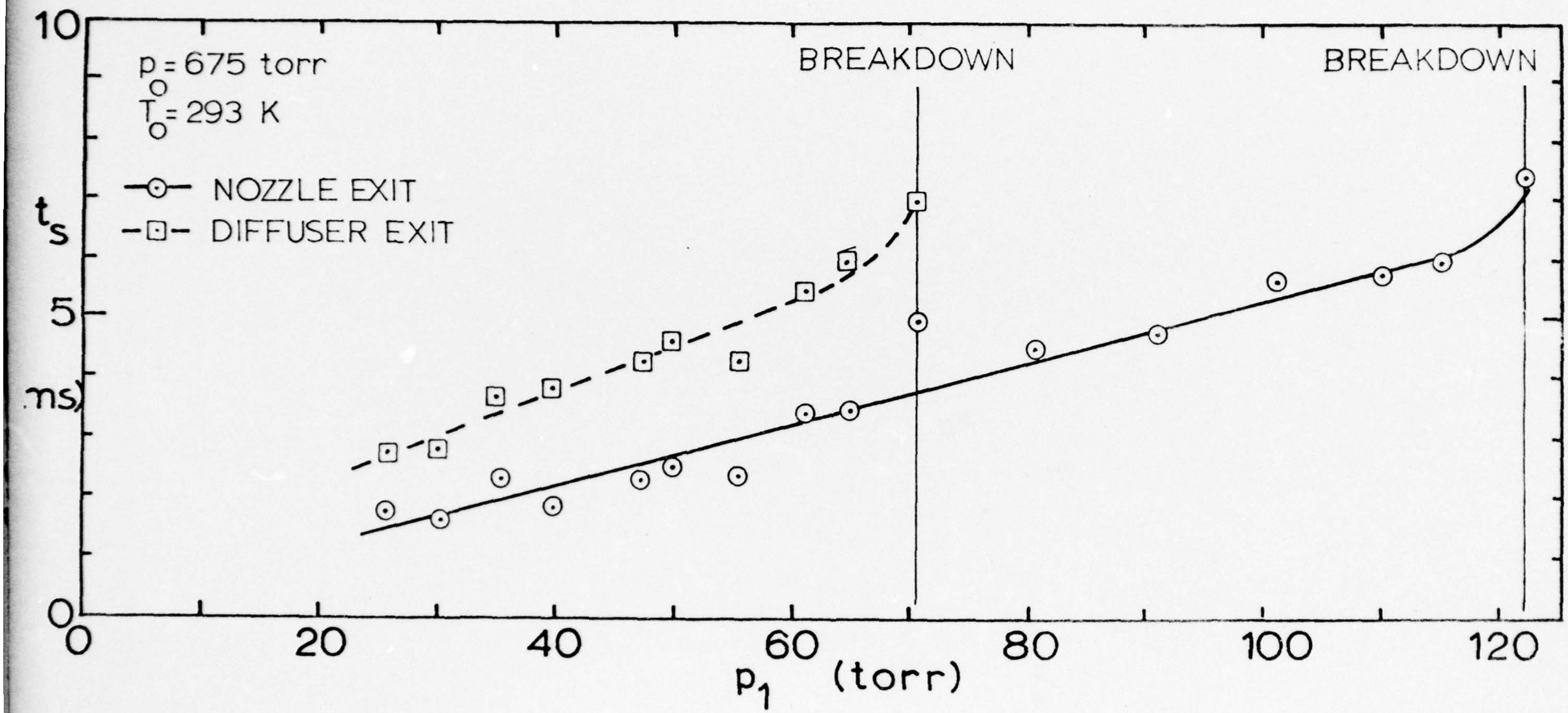


Figure 20. Starting times for the flow at the nozzle and diffuser exits as a function of initial downstream pressure, p_1. Diffuser length, L/D = 6. Upstream diaphragm location. Nozzle entrance at 1.81 in from diaphragm.

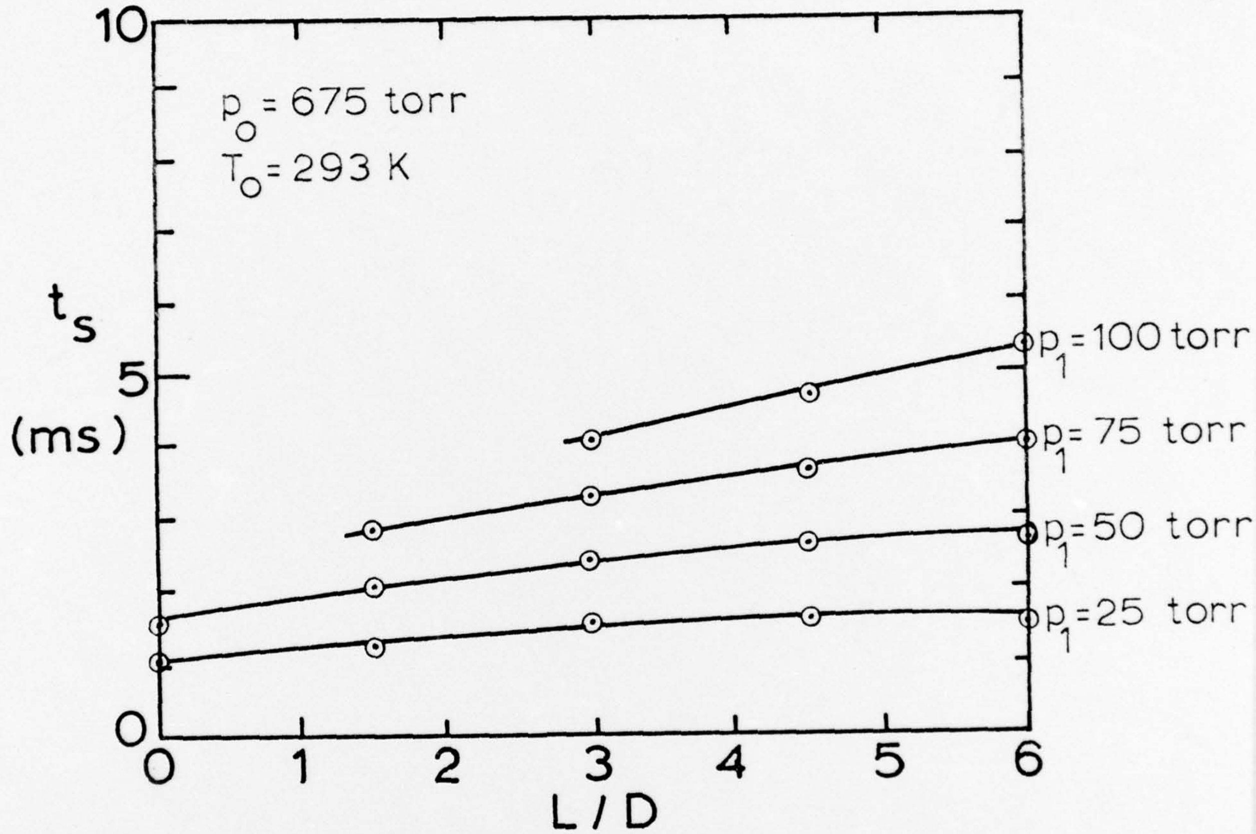


Figure 21. Starting times for supersonic flow at the nozzle exit as a function of dimensionless diffuser length, L/D, for various initial downstream pressures, p_1. Upstream diaphragm location. Nozzle entrance at 1.81 in from diaphragm.

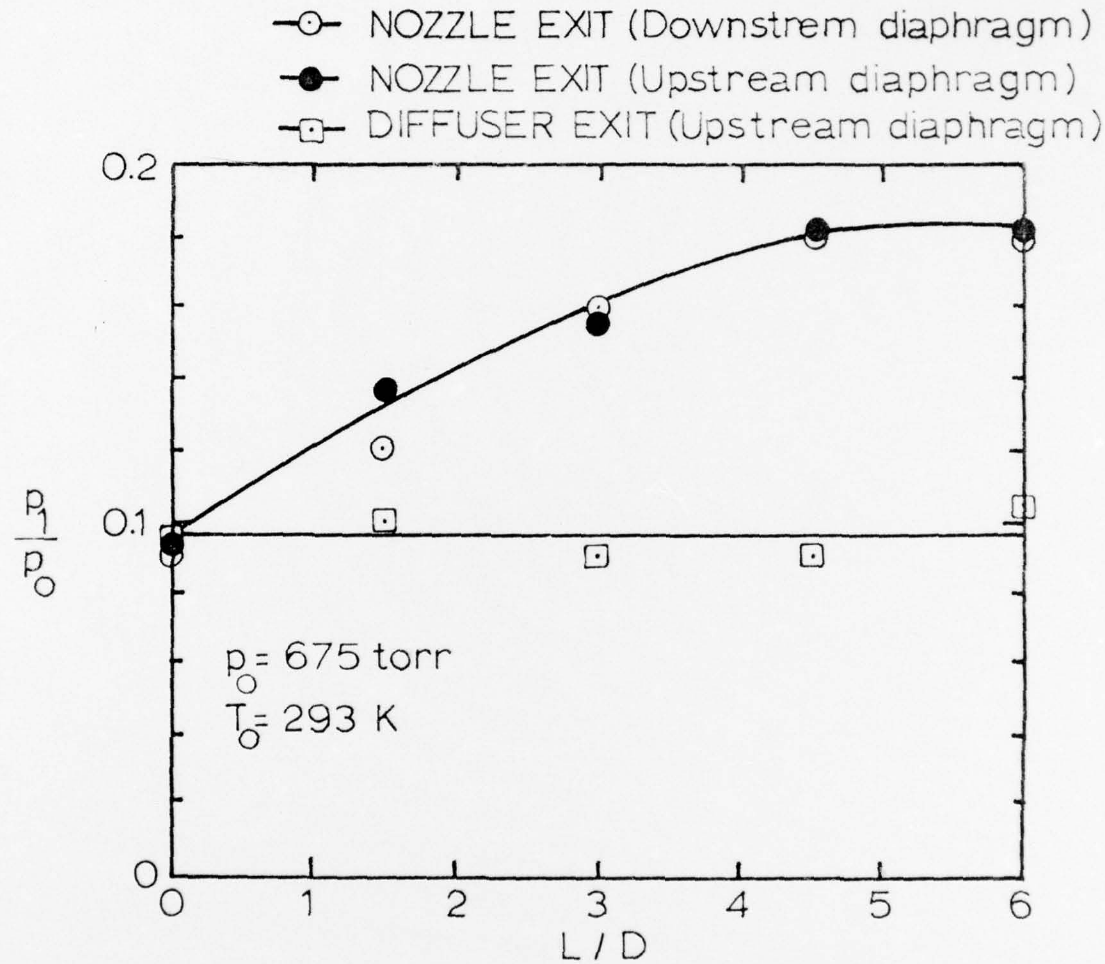


Figure 22. Optimum pressure ratio (p_1/p_0) for the supersonic flow to start properly in the nozzle and diffuser exits as a function of the dimensionless diffuser length, L/D. Both upstream and downstream diaphragm locations.

REPORT DOCUMENTATION PAGE

1. REPORT NUMBER: AFOSR - TR - 76 - 1236

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): THE FLOW STARTING PROCESS IN CONSTANT AREA SUPERSONIC DIFFUSERS IN A LUDWIEG TUBE

5. TYPE OF REPORT & PERIOD COVERED: Interium

6. PERFORMING ORG. REPORT NUMBER: Report #5

7. AUTHOR(s): Peter E. Merkli and Nesim Abuaf

8. CONTRACT OR GRANT NUMBER(s): F 44620-73-C-0032

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Department of Engineering and Applied Science, Yale University, New Haven, CT 06520

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: ~~681307~~ 9781-03 61102F

11. CONTROLLING OFFICE NAME AND ADDRESS: AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA, BLDG 410, BOLLING AIR FORCE BASE, D C 20332

12. REPORT DATE: September 1976

13. NUMBER OF PAGES: 52

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Diffusers, supersonic
Flow starting
Ludwieg tube
Pressure recovery

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A Ludwieg tube with a diaphragm located either upstream or downstream of the test section was used to investigate starting times of flow in a $M = 3$ nozzle followed by a constant area diffuser of square cross section (2×2 in^2) with length $0 \le L/D \le 6$. The test conditions were $M = 2.8$, $Re_D = 3.6 \times 10^5$, $\delta^*/D \sim 0.04$.* next page

*See nomenclature on page v.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

In the present work the starting time of the supersonic flow at a given location in the supersonic part of nozzle and test section is defined as the time interval required to establish the steady state pressure by a transducer at the same point, after the initial expansion fan (downstream diaphragm location) or shock wave (upstream diaphragm location) arrives at that point.

cont. For a downstream diaphragm location the starting times were found to be dependent on the diffuser length, but independent of the initial pressure ratio across nozzle and diffuser, as long as this ratio was low enough to allow supersonic flow to be established. For the upstream diaphragm location, the starting times were much shorter than those for downstream diaphragm location. In this second situation, the starting times, however, increased with the pressure ratio across the entire nozzle-diffuser section. For both upstream and downstream diaphragm locations the starting times for supersonic flow at the nozzle exit were longer for the longer diffusers. The lowest overall pressure ratio needed for the flow to start was about 1.2 times the value of the optimum operating pressure recovery ratio for steady flow. The latter ratio was found in previous experiments in a smaller continuous wind tunnel with a geometrically similar nozzle and diffuser. The required diffuser length ~~(L/D ~ 4.5)~~ for starting at the optimum pressure ratio corresponds to the expected recovery length of the diffuser as derived from the earlier work with steady flow.